Highway Lane Management Policy for Existing and Connected Autonomous Vehicles

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Highway Lane Management Policy for Existing and Connected Autonomous Vehicles

by

Md Mokaddesul Hoque

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Dedication

To my wife – Sifat Parveen Sheikh
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Abstract

Trucks carry major bulk of freight in the U.S. and are likely to continue doing so in the near future for various reasons. They have tremendous impact on highway pavement design and on the costs of pavement construction, maintenance, and rehabilitation. Current policy of truck lane restriction ensures that they mostly use the outside lane(s) on multilane highways. This practice has considerable impact on the cost of pavement construction and rehabilitation. Right now, all the highway lanes are designed and constructed according to the truck load on the outside lane even though the inside lanes receive significantly smaller quantity of load from truck movement compared to the outside lane. The overall construction and rehabilitation cost of highway is clearly influenced by this design uniformity of highway lanes. Comparison of this practice with a group of alternative policy options for flexible pavement shows that the current policy costs much more for the construction of flexible pavement. It is possible to reduce highway pavement life cycle cost by distributing the trucks across the available lanes. But further cost reduction can be achieved by designing and constructing each lane according to the quantity of truck traffic it receives, not the quantity of truck traffic on the outside lane (design lane). Comparable cost reduction can also be achieved by separating truck lanes from the lanes for passenger cars.

Future highway lane management policy will potentially be different from the existing to exploit the benefits of truck platooning to the fullest possible extent. Current literature and results from testing at different parts of the world suggest that the vehicles of future highway system are
likely to be connected and autonomous and would be able to form platoons to reduce fuel consumption cost and enhance safety. Within the existing highway lane management policy only limited quantity of truck platooning can be achieved. The possible lane management policy approaches that can allow high degree of truck platooning for connected and autonomous vehicles are assessed for construction, rehabilitation, and fuel consumption cost. One of the possible policy approaches to promote truck platooning is to lift truck lane restriction in the future and direct the truck platoons to use one of the inside lanes of multilane highway segments. If there is higher demand for truck platooning, not achievable with one lane, more lanes can be made available for truck platoons. Opening all the available lanes with high demand for truck platoons can also allow the trucks to assess the possible gaps for the platoon at a certain time and then choose the most suitable lane. In the opposite realm of choices is the conservative approach of allowing some quantity of truck platooning on the outside lane when there is available space headway for the platoons to operate without hampering the movement of entering and exiting vehicles on the outside lane. Choice of lane management policy to promote truck platooning movement can produce very different platoon formation from a range of most basic platooning with two vehicles to full scale platoons with many trucks moving together like a road train. This possible range of platoon formation has an associated range of costs for fuel consumption. Also the flexible pavement construction and rehabilitation cost changes depending on how the platoons are being operated with the choice of lane management policy approach. Assessment of future highway cost elements shows that promotion of truck platooning can reduce the flexible pavement construction/reconstruction cost for unit length of highway as it requires some distribution of trucks from the outside lane. Fuel consumption cost also decreases with increasing quantity and degree of truck platooning. Promotion of truck platooning by changing lane management policy
approach increases flexible pavement rehabilitation cost to some extent but is a small fraction of the construction/reconstruction cost. Addition of a separate truck-only, platoon-only lane to the highway ensures further reduction in fuel consumption cost of the trucks. But a new lane would mean more cost for the construction, rehabilitation and right of way. Cost assessment for unit length of a six-lane highway with 8000 annual average daily truck traffic (AADTT) shows that the cost of fuel consumption reduction from the movement of truck platoons on the additional lane is higher than the combined yearly cost of construction, rehabilitation, and right of way for the additional lane. This suggests that there is financial incentive to consider tolled truck-only lanes in the future to promote truck platooning to its fullest possible extent.

This research shows a methodology to find out three important cost components (flexible pavement construction/reconstruction, rehabilitation, and fuel consumption) that would be largely affected if the lane management policy approach is updated for taking advantage of the connected and autonomous vehicles. Similar steps can be followed to find out if there is room for dynamically updating lane management approach in the future. A possible example of dynamic lane management approach would be allowing very limited truck platooning during the peak period on the outside lane of a multilane highway but allowing more truck platooning to take place on the inside lanes during the off peak hours. Another dynamic lane management approach example can be provided with the truck-only lane. The truck-only, platoon-only lane can accommodate some passenger cars during the peak hours and can again be made truck-exclusive for the rest of the day. Communication of such policy changes should be quite easy for future vehicles as they would be connected to each other and with the infrastructure. Probable cost trends for accommodating truck platoons in a highway segment have been reported here with one volume of trucks for a six-lane highway. Future studies can be conducted for different volume and lane configurations to
understand the general nature of life cycle cost in large presence of connected and autonomous vehicles.
Chapter 1: Introduction

Among different modes of freight, truck dominates in the U.S. by many means. Trucks carried 67 percent of freight value in 2007, which rose to 69 percent in 2013 (Chambers et al., 2015). The U.S. Departments of Transportation (DOT) estimates suggest continuation of truck dominance in the future. In 2040, truck share of shipment value is estimated to be 66 percent. Taking shipment weight into consideration instead of value, trucks carry nearly 70 percent of tonnage among trips shorter than 750 miles (Chambers et al., 2015). Future truck tonnage may exceed the current estimates with large-scale adoption of autonomous and connected vehicles by trucking industry. The quantity of truck travel significantly affects pavement design and subsequent performance. Percentage of trucks within traffic stream is an important consideration in pavement design. Higher truck percentage generally leads to higher expenses in pavement construction, rehabilitation, and maintenance.

Construction and maintenance of highways are quite costly. According to a 2013 status report from U.S. Department of Transportation, in 2010, the U.S. spent 33.4 billion dollars in maintenance of highways and additional 100.2 billion dollars in roadway capital (new construction, reconstruction, resurfacing, restoration, etc.). Cost of roadway maintenance is generally going up but there remains a huge gap between funds necessary for maintenance, system enhancement, system expansion and the actual expenditure. According to the American Society of Civil Engineers (ASCE) road infrastructure report card 2017, the backlog for repairing existing highways alone was $420 billion. By their estimates, this gap is likely to increase significantly in
the years ahead. Given this backdrop, there are grounds to review existing roadway design and truck lane use pattern to minimize future roadway construction and maintenance costs.

Current regulatory policies require enhancement in freight movement along highways. Automation of trucks is one probable way to reach that goal. Freight routes are now considered separately as part of National Highway Freight Network (NHFN). This network is defined in Fixing America’s Surface Transportation Act (FAST). Map of NHFN will be updated in every five years which will consist of highways that would require improved performance in terms of safety, congestion, project delivery, etc. Current map of NHFN consists of 41,518 centerline miles, including 37,436 centerline miles of Interstate and 4,082 centerline miles of non-Interstate roads. Autonomous and connected trucks promise enhanced safety and reduced congestion. So government initiatives to enhance performance along these routes via federal and state projects may be complemented by current interest and enthusiasm of trucking industry to invest in automation and connectivity.

Autonomous and connected trucks promise leap in safety, productivity, and fuel savings. Even if a good fraction of these promises is met, there should be sizable increase in truck mode share within next one or two decades. For design and construction of pavements, this means more truck loads on certain lanes of highways. Besides increase in truck traffic quantity, some notable future changes due to modification of vehicle technology would be spacing between travelling trucks, hourly use pattern, and lateral wandering of wheels. It is not clearly known how these future changes would affect the cost of highway construction and maintenance. Highway agencies would not want to widen the gap between highway maintenance fund requirement and availability in the future. This dissertation is intended to explore if the potential upgrades of vehicles technology can be exploited to reduce highway agency costs or at least to keep the costs at existing level.
1.1 Autonomous and Connected Vehicle Technology

There is no global consensus yet on terminologies that define autonomous driving. Ozguner et al., 2011 defined autonomous vehicles with significant simplicity: “We define ‘autonomy’ in a car as the car making driving decisions without intervention of a human.” This is a broad, generic definition. Authors within this broad definition consider all probable aspects of autonomous driving: vehicles that are partially automated but unable to drive independently, fully autonomous vehicles unable to connect to each other and vehicles that are capable of communicating with each other.

U.S. DOT website defines autonomous vehicles as an extension of automated vehicles, and includes connected vehicles within that range. “Automated vehicles are those in which at least some aspect of a safety-critical control function (e.g., steering, throttle, or braking) occurs without direct driver input. Automated vehicles may be autonomous (i.e., use only vehicle sensors) or may be connected (i.e., use communications systems such as connected vehicle technology, in which cars and roadside infrastructure communicate wirelessly). Connectivity is an important input to realizing the full potential benefits and broad-scale implementation of automated vehicles.” Platooning is not defined as clearly. Overall, these terms are used here throughout the dissertation. Additionally, ‘connected autonomous vehicle (CAV)’ is used for vehicles capable of connecting with other vehicles or infrastructure and are autonomous. It is assumed that connected vehicles are capable of platooning as long as they are connected irrespective of the driver being human or robot.

Ozguner et al., 2011 sometimes termed autonomous vehicles as ‘Autonomous Intelligent Vehicles’. Both Litman, 2015 and Fagnant & Kockelman, 2015 used a generic term ‘autonomous vehicles’ that includes both autonomous vehicles and connected vehicles. ‘Platooning’ has been
assigned for vehicles capable of communicating with each other and forming a convoy (so it is an
available feature of connected vehicles, among many).

National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive
Engineers (SAE) International separately define autonomous vehicles in different steps depending
on how much driving task is assigned to machine from human driver. NHTSA definition is
presented in Table 1.1.

Table 1.1 Levels of vehicle automation (NHTSA, 2019)

<table>
<thead>
<tr>
<th>Level of Automation</th>
<th>Extent of driving performed by machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td>No automation; driver performs all tasks</td>
</tr>
<tr>
<td>Level 1</td>
<td>Driver assistance; some driving assist feature in vehicle design</td>
</tr>
<tr>
<td>Level 2</td>
<td>Partial automation; vehicle has combined automated functions, but driver must remain engaged with driving task and monitor environment</td>
</tr>
<tr>
<td>Level 3</td>
<td>Conditional automation; driver is necessary, but not required to monitor environment and ready to take control if needed</td>
</tr>
<tr>
<td>Level 4</td>
<td>High automation; vehicle capable of all driving functions under certain conditions, driver may have option to control vehicle</td>
</tr>
<tr>
<td>Level 5</td>
<td>Full automation; vehicle capable of driving under all conditions, driver may have option to control vehicle</td>
</tr>
</tbody>
</table>

It is important to note that these levels or similar definitions from SAE do not make
distinction between autonomous and connected vehicles. The focus was to differentiate roles for
human driver and machine, irrespective of driving behavior of the vehicle. For the analysis that
follows in this dissertation, at least Level 4 automation was assumed for platooning of connected and automated vehicles.

1.2 CV and Platooning

According to the U.S. Department of Transportation, 2019, connected vehicle technology will enable vehicles (V2V), roads and other infrastructure (V2I), and smartphones to communicate and share vital transportation information in future. The communication flows will be based primarily on a networking technology known as dedicated short-range communications (DSRC), which is similar to Wi-Fi. DSRC offers unique opportunities for fast, secure, and reliable communications, and is not vulnerable to interference. With use of DSRC, equipment will continually transmit vehicle position, direction, and speed as well as other information, to vehicles sharing the road. It will even "talk" to equipment installed in the road itself and other infrastructure, such as traffic signals, stop signs, tollbooths, work or school zones, and railroad crossings. Following distance between vehicles may vary depending on various connectivity issues. Bergenhem et al., 2012 reported that distance between different platooning demonstrations projects varied between four meters to fifty meters.

Platooning is an application of Intelligent Transportation System (ITS) heavily dependent on V2V and V2I communication. This allows vehicles to follow each other quite closely compared to existing vehicles, ensuring fuel savings, safety enhancement and capacity increment of roadway. Bergenhem et al., 2012 reported that the tests of platooning carried out so far were sometimes done in mixed traffic involving truck and lighter cars, otherwise in a dedicated lane with just trucks. Table 1.2 extracts some information from Bergenhem et al., 2012 and offers a summary of test features. Demonstrations in mixed traffic suggest some platooning probability without availability of dedicated lane(s).
### Table 1.2 Platooning demonstration goals and test conditions

<table>
<thead>
<tr>
<th>Project</th>
<th>Test Location</th>
<th>Vehicle Type</th>
<th>Lane Use</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>SARTRE</td>
<td>Europe</td>
<td>Mixed</td>
<td>Mixed, traditional</td>
<td>Comfort, safety, congestion, energy</td>
</tr>
<tr>
<td>PATH</td>
<td>CA, USA</td>
<td>Cars, Trucks</td>
<td>Dedicated</td>
<td>Increased throughput per lane, energy saving</td>
</tr>
<tr>
<td>GCDC</td>
<td>Netherlands</td>
<td>Mixed</td>
<td>Mixed</td>
<td>Deployment of cooperative driving system</td>
</tr>
<tr>
<td>Energy-ITS</td>
<td>Japan</td>
<td>Trucks</td>
<td>Dedicated</td>
<td>Mitigate lack of skilled driver</td>
</tr>
<tr>
<td>SCANIA</td>
<td>Europe</td>
<td>Trucks</td>
<td>Mixed, traditional</td>
<td>Commercial fleet, energy</td>
</tr>
<tr>
<td>Highway Pilot</td>
<td>Germany</td>
<td>Trucks</td>
<td>Mixed, traditional</td>
<td>Safety, energy</td>
</tr>
<tr>
<td>Connect, Daimler</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.3 Truck Automation

Automation of trucks is generally discussed as a special condition of AVs within freight section. To some, freight automation means carrying goods at sizably cheaper rates than existing ones. This, in effect, may lead to increase in vehicle miles travelled by trucks.

Bishop, 2005 suggested that truck automation is more urgent from safety and economic standpoint compared to passenger cars. Value of payload and accident cost can be key drivers for development for truck automation. Recent publications also have very optimistic timelines for truck automation for similar reasons. Figure 1.1 shows that full automation is followed by deployment of platooning as early as 2025.
Smith, 2015 suggested that vehicle-to-vehicle communication is a key requirement for truck platooning. The behavior of the first vehicle, such as braking and steering, should be transmitted by vehicle-to-vehicle communication. The function should also smoothly handle vehicles leaving the platoon. Dedicated “perpetual” truck platoons that allow vehicles to join and leave at specified stations could also prove an interesting future application of this technology for long-distance motorway trips. Up-scaling and deployment can be reached as follows:

- Start with trucks, as there is a strong financial incentive due to 10% to 15% fuel savings.
- Start with small platoons of only two trucks and co-operation with fleet-owners in high density trucking areas.
- For legal reasons, start with a system where the following truck still has a driver in it.
- Set up an (open) fleet management system for trip matching between equipped trucks of different fleet owners.
1.4 Truck Automation Incentives

Shanker et al., 2013 predicted that annual savings from adoption of large-scale autonomous trucks (which includes connected trucks as well) can be as much as 168 billion dollars. Biggest share of 70 billion dollars may come from savings in labor followed by fuel efficiency, road safety and productivity gains. Table 1.3 provides further details of savings.

Table 1.3 Financial gains of truck automation (Shanker et al., 2013)

<table>
<thead>
<tr>
<th>Saving source</th>
<th>Yearly Savings, billion USD</th>
<th>Assumptions and inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Savings</td>
<td>70</td>
<td>i. Number of drivers will be significantly less than current situation. Roughly, two third of current cost will be incurred annually</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. Recruitment cost will be lot lower since current annual turn-over rate is over 100% in industry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. Overall, 50% reduction of current expenditure</td>
</tr>
<tr>
<td>Accident savings</td>
<td>36</td>
<td>90% of current accidents are due to human error</td>
</tr>
<tr>
<td>Fuel efficiency gains</td>
<td>35</td>
<td>i. US truck fleet drove around 400 billion miles in year 2011. Fuel economy of truck fleet is 7 gallons per mile.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. 20% fuel efficiency can be achieved overall.</td>
</tr>
</tbody>
</table>
Table 1.3 (Continued)

<table>
<thead>
<tr>
<th>Saving source</th>
<th>Yearly Savings, billion USD</th>
<th>Assumptions and inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>27</td>
<td>i. Most prominent savings will come from fleet productivity since day-night operation can be continued whenever needed.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii. 30% capacity increase overall.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iii. Elimination of congestion.</td>
</tr>
</tbody>
</table>

The authors acknowledged at the beginning of the analysis that the predictions are more like brainstorming results than data driven analysis. In reality, numerous macroeconomic factors will influence savings figures from automation of trucks depending on level of technology. More precise thought process and data-intensive analysis will most likely lead to a different sum from the one provided here. For example, there is lack of consensus regarding fuel savings from platooning. Another example is congestion. Elimination of congestion may not happen readily; only after the system has been improved over time and when all or most vehicles are autonomous.

Maurer et al., 2016 identifies four advantages over current scenario that may lead to truck automation: shortage of human drivers at low cost, lower fuel consumption (roughly 5% for leading vehicle and 10%-15% for following vehicles while platooning), higher reliability, and avoidance of accidents. The authors are optimistic about efficiency gains from increase in truck miles. Further gains are possible from capacity enhancement of roadways from close following of autonomous trucks. This study predicts change in supply chain management due to adoption of
technology. Lockridge, 2016 reported that price of freight movement would fall by half by 2030 due to automation of trucks.

1.5 Lane Separation for Autonomous Trucks

Existing literature favors separation of automated trucks. These studies did not generally explore pavement performance and associated life cycle cost. Fagnant & Kockelman, 2014 predicted that introduction of autonomous trucks would require new or modified infrastructure with dedicated platoon lanes and thicker pavements to handle high truck volumes. Maurer et al., 2016 suggested two infrastructure alternatives for safe implementation of these options: use of separate exits and entries for autonomous vehicles into the highway system, complete separation via dedicated lanes for autonomous vehicles.

Shladover, 2010 favored dedicated lanes for automated trucks. The advantages are not analyzed in detail, instead were depicted as scenario analysis as a function of automation technology progression. Most prominent reasons in favor of separation of trucks include safety of both trucks and passenger cars, economic benefit of longer-combination-trucks, smooth traffic flow for both light and heavy vehicles. The author briefly mentioned pavement aspect of separation without any comparative study. Since heavy trucks impose much more severe wear and tear than passenger cars on highway pavements and structures, there is a great potential for saving on the construction and maintenance costs of running ways (lanes) that are only used by passenger cars, while the heavy-duty designs and materials can be reserved for the trucks’ running ways.

1.6 Research Objectives

The overall objective of this research is to understand how lane management policy for heterogeneous vehicles (due to presence of passenger cars and trucks in the highway) impacts prominent life cycle cost elements of the flexible pavement in present context and in future with
availability of automated driving. This overall objective can be broken down into five specific research objectives.

Our first objective was to understand the relationship between the existing lane management policy for heterogeneous vehicles and the cost of flexible pavement. This is an important question because the pavement design and construction cost is largely dependent on the current policy of truck lane restriction and the concept of ‘design lane’ for pavement construction. Highway agencies often face shortage of funds necessary to maintain the highway system and also to expand the system. Clear knowledge of this relationship can help the agencies to reduce the cost of highway construction and maintenance.

The second objective was to assess a set of alternatives to the current highway lane management and pavement design policy. Our aim here was to assess the major cost elements during the life cycle of flexible pavement which includes construction and rehabilitation cost. As the right of way requirement for different policy alternatives were not same, we also wanted to understand if the inclusion of right of way cost would affect the cost comparison of the alternatives.

The third objective was to scan the potential future lane management policy options and find out how they would compare in terms of pavement cost and fuel consumption benefit. This is an important question as there are a good number of publications that predict connected and autonomous vehicles becoming a reality quite soon and reaching a dominant market share within the next few decades. As the new vehicles take over the task of driving from humans to some extent or to the full extent, the highway agencies will potentially update the lane management policy approach in future. We wanted to compare the costs of these future policy approaches and provide a glimpse of the future cost scenario for the highways as we move towards the connected and autonomous vehicle era.
The fourth objective was to compare the future lane management policy approaches in terms of user benefits. One of the most encouraging feature of these futuristic vehicles is the capability of forming platoons to reduce fuel consumption and enhance safety. We wanted to assess the fuel consumption benefits across different lane management policy approaches and compare the benefits to the associated costs of highway construction and maintenance.

Our final objective was to understand if the truck-only lanes approach have any cost advantage in the current scenario and in future with the availability of connected and autonomous vehicles. This policy approach has been assess from different angles in literature but the assessment of life cycle cost has been overlooked. Additionally we wanted to understand the scale of fuel consumption benefit possible from truck platooning to know if the benefit can be exploited for construction and maintenance cost of additional truck platooning lanes in the highway system.
Chapter 2: Effect of Highway Lane Management Policy of Human Driven Trucks on the Cost of Flexible Pavement

2.1 Executive Summary

Truck lane restriction is one of the most common highway lane management strategies, which ensures that heavy vehicles mostly use the outer lanes of a multilane highway. Higher percentage of heavy vehicles in the design lane increases required load bearing capacity of the pavement structure and essentially, construction cost. This study considers three probable strategies to control this cost trend for flexible pavement: distribution of trucks across multiple lanes, design of heterogeneous pavement structures across lanes, and separation of car lanes from truck lanes. It is found that the construction cost of one unit length of highway is less for each strategy than the cost incurred with the restriction in place. Cars and trucks may not continue to use highway lanes in the traditional way to take advantage of platooning. Cost advantages reported here can be exploited for selecting future highway lane management strategies in the environment of connected and autonomous vehicles.

2.2 Introduction to Existing Lane Management Policy

Trucks generally use the outside lane(s) on multilane highways. In most U.S. states, there is some form of restriction in place to ensure that trucks stay away from the inside lane(s). This common practice is discussed here as “truck lane restriction”. Such practice causes the outside

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lane(s) to carry much more heavy traffic than the inside lane(s). Higher presence of trucks in one lane leads to the requirement of higher load bearing capacity from the design lane. Consequently, all the lanes are costlier to construct or reconstruct since the same pavement structure is generally applied to all lanes. During the use phase of highways, lanes with a higher share of truck loads may deteriorate faster than the lanes with medium or low shares of truck loads. However, roads do not damage due to truck load only, there are severe impacts from environment as well. Relative degree of maintenance among the lanes does not have a universal practice since it depends on the extent of damage. In the end, all the lanes will typically be reconstructed according to the truck volume on a ‘design lane’ just like the case of initial construction. Such practices lead to conservative pavement designs for inside lanes and, therefore, unnecessary increase in construction or reconstruction costs. Lifting these restrictions may reduce concentration of trucks on one/two lanes only. Distributing trucks across lanes has the potential to reduce the truck volume on the design lane, and eventually the highway construction or reconstruction cost. On the other hand, if truck lane restriction is meant to stay, it is a waste to construct all the lanes as though they would be subjected to the same loading as the design lane when the reality is always otherwise. In light of emerging technology of connected and autonomous vehicles, the former case is becoming more feasible. With access to all lanes, heavy vehicles may achieve and maintain uninterrupted and long truck platoons. Alternatively, dedicating one or two lanes for platooning will also distribute heavy traffic and is likely to reduce the number of heavy vehicles on the design lane. Vehicle connection and automation will potentially change the highway lane management strategies in place. Some future strategies may include: dedicated platoon lanes (Nowakowski et al., 2015; Chen et al., 2017), dedicated connected and autonomous vehicle lanes (Husain et al., 2016; Talebpour & Mahmassani, 2017), dedicated connected and autonomous truck lanes (Fagnant
It is undecided which specific highway lane management strategy or set of strategies will prevail with changes in vehicle and infrastructure technologies, but most of them will lead to considerable deviation from the current truck lane restriction. Work presented in this chapter is intended to quantify flexible pavement construction cost under two scenarios: when trucks are distributed across available highway lanes and when pavement design of highway lanes is proportionate to actual number of trucks to efficiently accommodate truck lane restriction practice. Additionally, the chapter is aimed at evaluating construction cost of highways when trucks and cars use dedicated lanes unlike the mix currently observed on most highways.

This chapter begins with the comparison of multilane highway pavement designs for varying degree of heavy truck presence on the design lane in order to understand the relationship between degree of truck lane restriction and pavement design. Then a set of probable highway lane management approaches besides the current approach is explored in terms of pavement design. Cost comparison of these alternatives with the existing design method emphasizes the importance of innovations in the future pavement designs to ensure efficient use of resources.

2.3 Literature Review

Effects of highway lane management policy is commonly reported from capacity and safety perspective instead of pavement design or construction/maintenance cost perspective. There are few studies on truck lane restriction practice. The available literature is discussed briefly in this section. Mannering et al., 1993 reported common reasons for implementing truck lane restrictions. Most significant reasons include improvement of highway operations, road safety, even distribution of pavement wear, and restriction in constructions. Similar reasoning was provided by Jasek et al., 1997. Types of restrictions, as mentioned in both references, are different
at various locations. Four common types mentioned are lane restriction, route restriction, time-of-day restriction, and speed restriction. It is clear from both studies that the first type (lane restriction) is more common than the other three. Among the states that have imposed some form of restrictions, only few do it in order to equalize pavement wear while most states are for the other reasons mentioned above. Another common type, speed restriction, forces trucks to take outer lanes without being explicitly lane restriction type. Table 2.1 summarizes types of lane restriction in different U.S. states among the 37 reported by Mannering et al., 1993.). The study also showed that many of these states have more than one type of restriction in place.

Table 2.1 Truck lane restriction trend in different U.S. states (Mannering et al., 1993, page 24)

<table>
<thead>
<tr>
<th>Location</th>
<th>Lane</th>
<th>Route</th>
<th>Time</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arizona</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Arkansas</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>California</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Colorado</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Connecticut</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florida</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idaho</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illinois</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Indiana</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Iowa</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Kansas</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kentucky</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Louisiana</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maryland</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massachusetts</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michigan</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mississippi</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missouri</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nevada</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Jersey</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New York</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Carolina</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mannering et al., 1993 briefly analyzed the restriction effects on pavement. The analysis was for the scenario when all trucks comply with the restriction that trucks only use the right three lanes on a four-lane (in one direction) highway. It was assumed that resurfacing would be required when the Present Serviceability Index (PSI) reaches 1.5. Full compliance would mean no trucks on the inner lane (Lane 1) and somewhat increase in truck traffic on the adjacent lane (Lane 2). With redistribution of trucks across facility, Lane 2 (third from the outside for four lanes per direction) would reach that terminal PSI sooner due to additional truck traffic.

These predictions were made under certain assumptions. Most importantly among many is that traffic was the only reason for pavement deterioration while other influencing factors, such as weather, material property, construction quality, and maintenance frequency, were ignored. The analysis did not include any comparison between Lane 4 (outside lane with most truck traffic) and Lane 1 (inside lane with minimum truck traffic) though the difference in loading between these two would be large.
Another recent study assumed various truck distributions with truck lane restriction in place (Radhakrishnan, 2010). The Mechanistic Empirical Pavement Design Guide (MEPDG) software was used to predict damage of asphalt concrete layers under combined effects of environment factors and trucks. It was found that the difference in pavement damage with and without truck lane restriction is not statistically significant and therefore the effect of this practice on maintenance cost is negligible.

Some agencies tried to experiment with guiding trucks to left lanes to equalize pavement damage on all lanes. Findings from available few studies are mixed. Some reported reduced wear of pavements while others reported no significant difference in pavement maintenance.

Enforcement on trucks to use left lanes in Arkansas, as reported by Jasek et al., 1997, took place in two stages: the first one was along a particular route (I-40 west of Memphis), and the second was a statewide restriction. The statewide restriction was imposed in mid-1980s so that trucks could use more left lanes to even out pavement wear. It was not reported exactly how much of that aim was fulfilled or resulted in savings of maintenance cost. In reality, that restriction was not enforced and was discontinued due to lack of compliance. Gan and Jo, 2003 mentioned that trucks were prohibited from using the right lane on I-90/I-94 near Madison, Wisconsin to even out pavement wear as a temporary measure. Both Moses et al. (2007) and Gan and Jo, 2003 reported the reason for such restriction but neither mentioned further details of pavement effect or savings in maintenance cost (if any) from such restriction.

Mannering et al., 1993 reported findings from “Truck Lane Redistribution Test on an Interstate Highway” by Nevada Department of Transportation. It is important to note that ‘no long-term effects on pavement deterioration rates were studied’. For the short-term study, test sites were determined based on pavement condition with consideration of environmental effects and funding
availability for routine maintenance and improvements. It was observed that 60 percent of trucks voluntarily traveled on the left lane after erection of visible signs directing trucks to use the left lane. The Nevada research speculated extended life of five to ten years from projects completed close to the time frame when the test was conducted. Future construction, reconstruction, and overlays were expected to get reduced by 10 to 20 percent.

2.4 Effect of Truck Lane Restriction on Pavement Design

Truck lane restriction practice essentially puts more trucks on the design lane. Table 2.2 summarizes values of the Lane Distribution Factor (LDF) used for pavement design by various U.S. highway agencies. It shows that 4-lane highways are the most impacted group by this practice. Selection of high LDF values for pavement design leads to an increase in the pavement thickness or the use of materials with higher quality. Thus the cost of pavement construction/reconstruction goes up with LDF. Cost of maintenance may also go up depending on the choice of maintenance strategies. If the milling and resurfacing depth determined for the most affected lane is used for all the lanes, which is a common practice used by many highway authorities (Dawson et al., 2012), maintenance cost will vary with the degree of truck lane restriction. With such a strategy in place, extent of damage in the outside lane will dictate maintenance frequency and scale. This issue may be addressed by choosing separate resurfacing thickness for different lanes, depending on the extent of damage.

Table 2.2 LDF in different U.S. states as per pavement design manual

<table>
<thead>
<tr>
<th>State</th>
<th>LDF as a function of total highway lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Four lanes</td>
</tr>
<tr>
<td>Arizona</td>
<td>0.9</td>
</tr>
<tr>
<td>California</td>
<td>1.0</td>
</tr>
</tbody>
</table>
### Table 2.2 (Continued)

<table>
<thead>
<tr>
<th>State</th>
<th>LDF as a function of total highway lanes</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Four lanes</td>
<td>Six lanes</td>
<td>Eight (or more) lanes</td>
<td></td>
</tr>
<tr>
<td>Colorado</td>
<td>0.9</td>
<td>0.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td>0.85 – 1.0</td>
<td>0.7</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Idaho</td>
<td>0.7 – 1.0</td>
<td>0.6 – 0.8</td>
<td>0.5 – 0.75</td>
<td></td>
</tr>
<tr>
<td>Mississippi</td>
<td>0.9</td>
<td>0.6</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>New York</td>
<td>0.8 - 1.0</td>
<td>0.6 – 0.8</td>
<td>0.5 – 0.75</td>
<td></td>
</tr>
<tr>
<td>Ohio</td>
<td>0.95</td>
<td>0.8</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>South Carolina</td>
<td>0.8</td>
<td>0.65</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Texas</td>
<td>1.0</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Utah</td>
<td>0.9</td>
<td>0.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Virginia</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Wisconsin</td>
<td>0.95 – 0.85</td>
<td>0.65 – 0.5</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

In order to quantify the effect of truck lane restriction on pavement design, the thickness of asphalt concrete (AC) of typical flexible pavements was estimated in this study using different LDF values. The Average Annual Daily Truck Traffic (AADTT) value was ranged from 4000 to 22000. This range, taken from Underwood and Nagarajan (2015), covers most freight routes in the U.S. In addition to LDF and AADTT, other design factors used for estimating thickness of asphalt concrete are presented in Table 2.3. The AASHTO 1993 pavement design guide was followed for the estimation. The basic flexible pavement design equation is recalled here.
\[
\log_{10}(W_{18}) = Z_R * S_0 + 9.36 * \log_{10}(SN + 1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2 - 1.5}\right)}{0.40 + \frac{1094}{(SN + 1)^{0.19}}} \\
+ 2.32 * \log_{10}(M_R) - 8.07;
\]

and,

\[SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 + \cdots,\]

where \(W_{18}\) is the predicted number of 80 kN (18,000 lb) Equivalent Single Axle Load (ESAL); \(Z_R\) is the standard normal deviate; \(S_0\) is the combined standard error of the traffic prediction and performance prediction; \(SN\) is the structural number indicative of the total pavement thickness required; \(\Delta PSI\) is the difference between initial design serviceability index and terminal design serviceability index; \(M_R\) is the subgrade resilient modulus in psi; \(a_i\) is the \(i^{th}\) layer coefficient; \(D_i\) is the \(i^{th}\) layer thickness in inches; \(m_i\) is the \(i^{th}\) layer drainage coefficient.

Table 2.3 Material properties and other assumptions for estimation of asphalt concrete thickness

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>Basic Property/Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgrade</td>
<td>Resilient modulus,</td>
</tr>
<tr>
<td></td>
<td>(M_{Reff}: 103.42) MPa and 41.37 MPa</td>
</tr>
<tr>
<td></td>
<td>Thickness: 609.6 mm (24 inches)</td>
</tr>
<tr>
<td>Base</td>
<td>Resilient modulus: 193.05 MPa</td>
</tr>
<tr>
<td></td>
<td>Layer Coefficient: 0.15</td>
</tr>
<tr>
<td></td>
<td>Drainage coefficient: 1</td>
</tr>
<tr>
<td></td>
<td>Thickness: 254 mm (10 inches)</td>
</tr>
<tr>
<td>Asphalt Concrete</td>
<td>Resilient modulus: 3447.38 MPa</td>
</tr>
<tr>
<td></td>
<td>Layer coefficient: 0.44</td>
</tr>
<tr>
<td></td>
<td>Drainage coefficient: 1</td>
</tr>
<tr>
<td>Pavement Layer</td>
<td>Basic Property/Assumption</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Shared parameters</td>
<td>Z&lt;sub&gt;R&lt;/sub&gt; : -1.645 (95% reliability)</td>
</tr>
<tr>
<td></td>
<td>S&lt;sub&gt;0&lt;/sub&gt; : 0.5</td>
</tr>
<tr>
<td></td>
<td>ΔPSI: 1.5</td>
</tr>
<tr>
<td></td>
<td>Design life: 20 years</td>
</tr>
<tr>
<td></td>
<td>Annual growth rate: 4%</td>
</tr>
<tr>
<td></td>
<td>Design Speed 104.61 km/h (65 MPH)</td>
</tr>
<tr>
<td></td>
<td>Equivalency Factor for conversion of AADTT to ESAL: 1.05 (FDOT, 2014)</td>
</tr>
</tbody>
</table>

The estimation results are presented in Figures 2.1 and 2.2. The AC thickness was estimated for two separate values of sub-grade resilient modulus (to represent low and high subgrade support conditions): 41.37 MPa (6000 psi), and 103.42 MPa (15000 psi). These figures show that the AC thickness increases with increment of AADTT and LDF. Hence, the highest thickness range is required when both AADTT and LDF are high. For fixed AADTT, thickness requirement goes up with an increasing value of LDF.

Two linear regression equations have been estimated for AC thickness, as a function of AADTT and LDF. The estimated coefficients of the two independent variables and a constant term are presented in Table 2.4. The usual range of LDF is 0.9 to 0.8 for four-lane highways. The estimated LDF coefficient values show that reduction of this range to 0.6 to 0.5 can lead to reduction of asphalt concrete thickness requirement by almost 25.4 mm (1 inch).
Figure 2.1 Thickness of asphalt concrete layer as a function of AADTT and LDF (subgrade \( M_{Reff} = 41.34 \) MPa)

Figure 2.2 Thickness of asphalt concrete layer as a function of AADTT and LDF (subgrade \( M_{Reff} = 103.42 \) MPa)
Table 2.4 Estimated linear regression models for asphalt concrete thickness (millimeters)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Subgrade resilient modulus</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>132.5053</td>
<td>103.42 MPa (15000 psi)</td>
<td>0.94</td>
</tr>
<tr>
<td>AADTT</td>
<td>0.0038</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDF</td>
<td>65.9864</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>189.6975</td>
<td>41.37 MPa (6000 psi)</td>
<td>0.95</td>
</tr>
<tr>
<td>AADTT</td>
<td>0.0046</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDF</td>
<td>89.6259</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5 Pavement Design Alternatives and Cost Comparison

Three broad categories of design solutions (and associated lane management strategies) were considered to encounter truck lane restriction practice: (1) distribution of heavy trucks across lanes instead of accommodating most in one lane, (2) keeping the restriction in place but designing heterogeneous pavement structures for these lanes, and (3) separating truck lanes from passenger car lanes. To this end, the three pavement design alternatives were compared with the traditional pavement design.

It was assumed that a flexible pavement section consists of three layers: subgrade, base, and asphalt concrete. It was also assumed that the number of lanes and the pavement design for both highway directions is the same as is the case for most highways in U.S. Figure 2.3 shows relative difference among the alternatives. Assumptions associated with the alternatives are briefly discussed below.
2.5.1 Traditional

This alternative represents the existing condition. Heavy trucks mostly use the outside lane and all the lanes have the same pavement structure as the “design lane”. Assuming the initial construction cost or reconstruction cost for this alternative is $C_1$, for ‘L’ number of lanes in each direction, it can be written that:

$$C_1 = 2 \cdot L \cdot (AC_{11} \cdot ACR + B_{11} \cdot BR + EW \cdot EWR)$$  \hspace{1cm} (1)

where $L$ is the number of lanes per direction, $AC_{11}$ is the volume of asphalt concrete required for the design lane, $ACR$ is the unit price of asphalt concrete (including material, placement, compaction), $B_{11}$ is the volume of base material required for the design lane, $BR$ is the unit price
for base layer (including material, placement, compaction), $EW$ is the volume of earthwork required per lane, $EWR$ is the unit price for earthwork (including material, placement, compaction). Asphalt concrete and base price for the entire highway section can be expressed as:

$$AC_1 = 2 \times L \times AC_{11},$$

and

$$B_1 = 2 \times L \times B_{11},$$

where $AC_1$ is the volume of asphalt concrete required for all the lanes, and $B_1$ is the volume of base material required for all the lanes.

2.5.2 Distributed Load

It is assumed here that heavy trucks are distributed across all available lanes due to some form of intervention from the highway agency. One probable example is lifting truck lane restriction on certain rural routes where the passenger car volume is relatively low. The volume of trucks should still be higher in the outside lanes than in other lanes even if truck lane restriction is fully lifted, but significantly less than that in the previous alternative. Construction/reconstruction cost for this option, $C_2$, can be expressed as:

$$C_2 = 2 \times L \times (AC_{22} \times ACR + B_{22} \times BR + EW \times EWR)$$ (2)

where $AC_{22}$ is the volume of asphalt concrete required for the design lane, $B_{22}$ is the volume of base material required for the design lane. Again asphalt concrete and base price for the entire highway section for distributed load can be expressed as:

$$AC_2 = 2 \times L \times AC_{22},$$

and

$$B_2 = 2 \times L \times B_{22},$$

where $AC_2$ is the volume of asphalt concrete required for all the lanes, and $B_2$ is the volume of base material required for all the lanes.
2.5.3 Heterogeneous Lane Design

In this case, the lane use pattern of trucks is assumed the same as the one in the ‘Traditional’ alternative. Pavement design is the same on all lanes in the ‘Traditional’ alternative but varies for highway lanes in this case. Pavement layers were designed for each lane separately in accordance with the expected heavy truck presence during the design life. In order to make sure that all the lanes have the same total pavement thickness, reduction of the AC layer thickness was compensated with an increase in the base layer thickness when a lane expects less number of trucks (Figure 3). Construction/reconstruction cost for this alternative, $C_3$ can be expressed as:

$$C_3 = 2 \times \sum_{n=1}^{L} (AC \times ACR + B \times BR + EW \times EWR)$$

(3)

where $AC$ is the volume of asphalt concrete for each lane, and $B$ is the volume of base materials for each lane. Asphalt concrete and base price for the entire highway section for distributed load can be expressed as:

$$AC_3 = 2 \times \sum_{n=1}^{L} (AC \times ACR),$$

and

$$B_3 = 2 \times \sum_{n=1}^{L} (AC \times ACR),$$

where $AC_3$ is the volume of asphalt concrete required for all lanes, and $B_3$ is the volume of base materials required for all lanes.

2.5.4 Truck only Lanes

Lanes for heavy trucks and passenger cars are fully separated here. The total highway lanes are divided in two types: truck lanes for heavy vehicles and car lanes for passenger cars. It is assumed that at least two lanes per direction are required for each vehicle type to allow vehicle passing and conditions like lane closure in emergency. This alternative is therefore considered for eight or more lanes. Construction/reconstruction cost $C_4$ is calculated by Equation (4).
\[ C_4 = 2 \cdot L_T \cdot (AC_{41} \cdot ACR + B_{41} \cdot BR + EW_T \cdot EWR) + 2 \cdot L_C \cdot (AC_{42} \cdot ACR + B_{42} \cdot BR + EW_C \cdot EWR), \]

where \( L_T \) is the number of lanes for heavy trucks in each direction, \( AC_{41} \) is the volume of asphalt concrete required for the truck lanes, \( B_{41} \) is the volume of base materials required for the truck lanes, \( EW_T \) is the earthwork volume for the truck lanes, \( L_C \) is the number of lanes for passenger cars in each direction, \( AC_{42} \) is the volume of asphalt concrete required for the car lanes, \( B_{42} \) is the volume of base materials required for the car lanes, \( EW_C \) is the earthwork volume for the car lanes.

Volume of asphalt concrete and base materials for the truck lanes can be expressed as:

\[ AC_{41} = 2 \cdot L_1 \cdot AC_T, \]
\[ B_{41} = 2 \cdot L_1 \cdot B_T, \]

where \( AC_T \) is the volume of asphalt concrete for the design lane of trucks, \( B_T \) is the volume of base materials for the design lane of truck lanes. Volume of asphalt concrete and base materials, similarly, can be expressed as:

\[ AC_{42} = 2 \cdot L_C \cdot AC_C, \]
\[ B_{42} = 2 \cdot L_C \cdot B_C, \]

where \( AC_C \) is the volume of asphalt concrete for the design lane of cars, \( B_T \) is the volume of base materials for the design lane of car lanes.

Now the required combined volume of asphalt concrete for truck and car lanes, \( AC_4 \) can be expressed as the sum of \( AC_{41} \) and \( AC_{42} \); required combined volume of base materials for truck and car lanes can be expressed as the sum of \( B_{41} \) and \( B_{42} \); and required combined volume of earthwork can be found from the sum of \( EW_T \) and \( EW_C \).
2.5.5 Truck only Lanes with Additional Capacity

In order to match the demand difference between trucks and passenger cars, there can be additional car lanes besides two pair of lanes for each type. For most freight routes in the U.S., two truck lanes would be able to serve with reasonable level of service. However, the required number of car lanes for peak demand can be significantly higher than two. Cost estimation of this alternative and comparison with any other alternative would require inclusion of right of way acquisition cost since the total number of lanes is uneven across alternatives.

2.5.6 Cost Comparison

Now comparing Equations (1) and (2), it can be seen that \( C_1 > C_2 \), which can be easily derived from \( AC_{22} < AC_{11} \) when the same AADTT is assumed for both alternatives and all else are equal.

It should be mentioned that this relationship between \( C_1 \) and \( C_2 \) holds as long as the design lane carries more trucks than the other lane(s) and LDF is smaller for distributed load strategy compared to LDF for traditional strategy. In the extreme case when the design lane carries the same number of trucks for distributed load alternative as any other lane(s) or when LDF reaches its minimum value (e.g., 0.5 for 4-lane highway and 0.33 for six-lane highway), then the difference between \( C_1 \) and \( C_2 \) is maximum.

From Equations (2) and (3), assuming the same AADTT and all else being equal, it can be proven that \( AC_3 < AC_2 \) and \( B_3 > B_2 \), but \( ACR \gg BR \). Therefore, \( C_3 < C_2 \). This relationship holds only when the unit price of asphalt concrete is significantly higher than the unit price of base layer. Similar relationship can be proved with compensation of asphalt concrete with earthwork instead of base material.
Similarly, for Equations (2) and (4), assuming $EW \geq EW_4$, and the same AADTT and all else being equal, it can be proven that $AC_4 < AC_2$ and $B_4 < B_2$. Therefore, $C_4 < C_2$. This relationship between $C_2$ and $C_4$ holds as long as the number of total lanes between the two alternatives is assumed to be the same and half of the lanes are assigned to cars and the other half for trucks.

Comparison between Equations (3) and (4) depends on assumption of truck volumes in different lanes. Therefore, relative values of asphalt concrete and base layer volumes for individual lanes are tied to the traffic movement assumption on the lanes and no definite conclusions can be made.

### 2.6 Cost Comparison Example

#### 2.6.1 Initial Construction Cost

In this section, the construction costs of highways with the alternatives mentioned in the previous section are compared. For each alternative, the flexible pavement structure is designed with a design life of 20 years with three levels of AADTT (low, medium and high) at a 4% annual growth rate. The volume of heavy trucks for each level is associated with the total number of lanes of a highway. Most studies about freight movement reported AADTT without the number of lanes. It is assumed that the total number of lanes is high when both passenger car and heavy truck volumes are high. So, the number of lanes is increased when AADTT increases. To accommodate cases with high AADTT but low passenger car presence or vice versa, two AADTT levels were considered for different numbers of highway lanes. For example, we considered base AADTT 8000 for both four-lane and six-lane cases. This captured both effects of number of lanes and LDF on construction cost. Similarly, base AADTT of 14000 was considered twice as shown in Table 2.5.
<table>
<thead>
<tr>
<th>Volume level</th>
<th>Number of Lanes</th>
<th>Base AADTT</th>
<th>LDF for ‘Traditional’/’Heterogeneous lane design’</th>
<th>LDF for ‘Distributed Load’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>4</td>
<td>4000</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>6000</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>8000</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Low</td>
<td>6</td>
<td>8000</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Medium</td>
<td>6</td>
<td>10000</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>High</td>
<td>6</td>
<td>14000</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>14000</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Medium</td>
<td>8</td>
<td>18000</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>22000</td>
<td>0.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

To calculate the construction cost of highways, weighted average bid rates from the state of Florida were used (FDOT, 2017). Right of way acquisition costs and design costs were ignored. These costs are most likely equal for all the alternatives considered since the number of lanes is kept equal. The costs presented here are simplified versions in order to capture the difference between the alternatives. Figure 2.4 shows the thicknesses obtained for different lane management strategies and subsequent changes in thicknesses of asphalt concrete and base layer when base AADTT is 14000 for four-lane example.
Figure 2.4 Pavement layer thicknesses for base AADTT 14,000 (not to scale). ACT = asphalt concrete thickness; BT = Base Thickness; and SGT = Subgrade thickness

Figure 2.5 and 2.6 underscore the findings reported in the previous section. Construction cost per kilometer of highway is always highest for traditional pavement design compared to distributed load and heterogeneous lane design. For same amount of highway traffic, this is observed as most of the trucks use the design lane for traditional pavement design. As the number of trucks on design lanes decreases for distributed and heterogeneous lane design, load bearing requirement decreases for these two alternatives, and consequently the amount of pavement materials required per unit length of highway section.

Highway construction cost goes up with increase in number of lanes within same strategy. Comparison of 4 and 6-lane highways for an AADTT of 8000 in these two figures show that per kilometer construction cost is higher for highways with more lanes even though daily volume of trucks is same. These two lane configurations compare two highways with different passenger car demand during the peak hours. This comparison highlights the effect of total number of lanes on cost increase when both LDF and AADTT is fixed.
Figure 2.5 Cost comparison per km for a four-lane highway

Figure 2.6 Cost comparison per km for a six-lane highway
Figure 2.7 Cost comparison per km for an eight-lane highway

Figure 2.7 shows per kilometer construction cost comparison among all four strategies. For an 8-lane highway example in Figure 2.7, cost trends are similar to the previous two figures. This figure additionally shows that full separation of lanes between trucks and lanes lead to significant drop in construction cost. It should be noted that this drop is partly achieved by assuming two dedicated lanes for trucks and two dedicated lanes for passenger cars per direction. However, daily volume of passenger cars are much higher than trucks in most routes. To address this demand difference, another comparison was made with inclusion of two additional lanes for passenger cars. Figure 8 compares 8-lane construction cost for the first three strategies (traditional, distributed load, and heterogeneous lane design) with 12-lane (4 passenger lanes and two truck lanes per direction) construction cost for truck only lane strategy.
Right of way acquisition cost was included for all strategies in Figure 2.8 since the combined pavement width for the lanes are not the same across the strategies any more. The pavement changes depending on the number of travel lanes provided for each strategy. This figure shows that the truck only lanes strategy is still cost efficient relative to traditional or distributed load strategy for eight lanes. One probable explanation is that the difference in width between 8-lane highway and 12-lane highway compared here was only four times the lane width. Width of median and clear zone is assumed fixed for all strategies and are both considerably higher than the difference in width between 12-lane and 8-lane highway. Table 2.6 provides assumptions for the right of way acquisition cost at an average land price in Florida in 2016 (United States Department of Agriculture, 2017).
Table 2.6 Assumptions for calculation of right of way acquisition cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median width</td>
<td>18.29 meters (60 feet)</td>
</tr>
<tr>
<td>Clear zone width in each direction</td>
<td>28.65 meters (94 feet)</td>
</tr>
<tr>
<td>Lane width</td>
<td>3.66 meters (12 feet)</td>
</tr>
<tr>
<td>Additional lanes for future expansion</td>
<td>2 lanes in each direction</td>
</tr>
<tr>
<td>Farmland real estate acquisition</td>
<td>45%</td>
</tr>
<tr>
<td>Cropland acquisition</td>
<td>45%</td>
</tr>
<tr>
<td>Farmland and building acquisition</td>
<td>10%</td>
</tr>
</tbody>
</table>

2.6.2 Life Cycle Cost Analysis

This section extends the cost comparison example of initial construction to Life Cycle Cost Analysis (LCCA) for an eight-lane highway of one km. The cases of four and six lane analysis are dropped to avoid repetition since the cost trends are similar to the eight lane example. Among the major components LCCA, it was assumed that two components varied significantly during the service life of pavement: initial construction and rehabilitation. The other components were ignored since both the combined vehicle volume and climate condition was unchanged across the alternatives being compared. A 20-year analysis period was chosen.

To estimate rehabilitation needs for each alternative during the analysis period, pavement performance predictions were made according to simplified pavement performance models (Lee et al. 1993). According to this empirical model, PSI during service year of the pavement is a function of initial PSI, existing pavement structure, age of pavement, cumulative ESAL and climate condition. For eight-lane highway, base AADTT at low, medium, and high level were
14000, 18000, and 22000. LDF values were also assumed to be similar to the example of initial construction. It was assumed that each lane would be rehabilitated separately, the year in which the initial PSI would drop from 4.5 to 3.0. The type of rehabilitation was milling and resurfacing of asphalt concrete with a design life of 10 years. Lanes that did not reach the terminal PSI of 3.0 within the service life of 20 years, 12.5 mm (0.5 inches) of resurfacing was applied in year 14 as a minimum. For the other lanes, the depth of resurfacing was found according to FDOT flexible pavement design manual (FDOT, 2018). Rate of milling was taken from the statewide average in 2016 (FDOT, 2016) and rate of asphalt concrete was taken from average FDOT bid rates in 2017 (FDOT, 2017). Rehabilitation costs incurred thus found were converted to Net Present Value (NPV) with an assumed discount rate of 3%. Finally, salvage value was deducted from the rehabilitation cost in case 10-year design period of rehabilitation was not met during the 20-year analysis period.

Figure 2.9 Rehabilitation cost comparison per km for an eight-lane highway
Figure 2.9 shows comparison of rehabilitation costs across the alternative design approaches for an eight-lane highways at three AADTT levels. Figure 2.10 shows similar comparison when truck only lane strategy has two additional lanes for passenger cars.

These two figures show that the rehabilitation cost trend is opposite to initial construction cost. Traditional alternative required the most conservative design and therefore required the least maintenance cost. Among the other design approaches, heterogeneous lane design required the least rehabilitation cost. Addition of car lanes for truck only lanes strategy does not increase rehabilitation cost significantly since the additional lanes does not carry heavy vehicles and requires minimum rehabilitation.
Finally, rehabilitation costs were added to the initial construction costs to find NPV of life cycle cost (LCC) for each alternative. Figure 2.11 and 2.12 shows LCC across different lane management strategies and subsequent design solutions.

![Figure 2.11 LCC Comparison per km for an eight-lane highway](image1)

![Figure 2.12 LCC comparison per km with additional car lanes in truck-only lanes alternative](image2)
These two figures show that the LCC trends are similar to initial construction cost. This happens because the rehabilitation costs are a substantially smaller segment compared to the initial construction cost. Increasing the analysis period should not change these trends since reconstruction cost is likely to be included in that case and would show similar trend as the initial construction cost.

2.7 Summary and Conclusions

Highway construction/reconstruction cost increases due to truck lane restriction. This is enhanced further with increased number of both heavy vehicles and passenger cars on a highway segment. Higher quantity of heavy vehicles leads to an increase in the required bearing capacity of pavement structures. Increased number of passenger of cars, on the other hand, leads to an increase in the required number of highway lanes. Both instances lead to increase in the cost of highway construction. Some of the highway lanes carry low volume of heavy traffic but are designed and built for a much larger load bearing capacity. Three different strategies are explored in this chapter in pursuit of higher cost efficiency from multilane highway pavement. Each strategy provides higher cost efficiency compared to the existing homogeneous design lane concept. Relative degree of cost savings among these three strategies would vary depending on site conditions and price of construction materials. Statewide weighted average contract price for Florida in 2017 has been used and it shows that heterogeneous lane design and truck only lanes provide higher cost efficiency compared to distributed load approach. Maintenance cost of unit length of highway decrease due to truck lane restriction when the lanes are maintained separately, based on pavement condition of each lane. Combination of these two opposing cost trends for LCCA in Florida condition shows that initial construction dictates the overall comparison due to difference in cost scale.
Chapter 3: Highway Cost Analysis for the Platooning of Connected and Autonomous Vehicles

3.1 Executive Summary

If connected and autonomous vehicles are sent to use the highways under current lane management policy, only partial benefit can be reaped from the platooning of advanced vehicles. The agencies may have to update the existing policy in the near future with regular presence of connected and autonomous vehicles on the highways. The probable management approaches are likely to affect highway construction, rehabilitation, and fuel consumption cost. Compared to a no-platoon approach, most of the approaches we considered reduce construction cost but increase rehabilitation cost for unit length of a highway. Fuel consumption cost decreases due to truck platooning for all possible approaches. If truck platooning is achieved by adding a separate truck only lane, the fuel consumption benefits are considerably higher.

3.2 Introduction and Literature Review

Technological advancements in vehicle connectivity, vehicle-infrastructure connectivity, and vehicle automation promise great benefits. Some of these benefits are enhanced safety, roadway capacity improvement, freight transportation productivity gains, and reduced energy consumption. Fulfillment of the promises requires transformation of existing vehicle fleet and infrastructure towards connectivity (and automation). Future vehicles are expected to be capable of communicating with each other and with the infrastructure besides the task of driving in part or in full. They should also be able to form platoon multiple vehicles to achieve lower fuel
consumption, safety enhancement, and productivity gain due to reduction of human involvement in driving task (Maurer et al., 2016). For the society to be able to harness aforementioned benefits, we need connected autonomous vehicles (CAVs) to move people and products at a higher efficiency compared to present level.

Efficient use of multilane highways requires lane management for heterogeneous vehicles (for present context passenger cars and trucks). Current lane management approach, in most U.S. states, is truck lane restriction. This approach ensures that heavy vehicles use the outside lane(s) (right side lanes in the U.S.) and light vehicles use the inside lane(s). It is unlikely that this would be the most efficient approach to use highways with CAVs becoming commonplace. Frequency and length of truck platoon, depending on the number of vehicles joined in the platoon, for example, will be limited with truck lane restriction in place for connected and autonomous trucks (CATs). For trucking industry this means inability to reduce fuel consumption possible with platooning. Janssen et al. (2015) used lengths of two regular tractor-trailers to explain that a platoon of two trucks can be 144 feet long assuming 23 feet space between trucks. Few lengthy blocks like that on the outside lane(s) will prevent easy maneuver of other vehicles since the outside lane(s) is also used frequently for entry/exit. Longer platoons (with more than two trucks) are likely to create further operational and safety related challenges for regular highway users (who are not interested to be part of a platoon) if they operate under existing lane management policy. Platoon of passenger cars will pose similar challenges but with less severity owing to size advantage and shorter space headway compared to trucks.

Various lane management approaches have been analyzed in the literature and most studies show that connected and autonomous vehicles can offer benefits with appropriate choice of lane management approach. Commonly discussed approaches in existing literature are: (1) Dedicated
CAV Lanes (Ghiasi et al., 2017; Talebpour & Mahmassani, 2017), (2) Dedicated Cooperative Adaptive Cruise Control (CACC) Lanes (Van Arem et al., 2006), (3) Dedicated Platoon Lanes (Amoozadeh et al., 2015; Nowakowski et al., 2015; Chen et al. 2017), (4) Dedicated CAT Lanes (Fagnant & Kockelman, 2014; Maurer et al., 2016; Shladover 2010), (5) Managed Lanes for CAVs (Chen et al., 2017; Ghiasi et al., 2017; Fakhar Qom et al., 2016) and (6) Lane Assignment of Platoons (Dao et al., 2008; Hall et al. 2005; Baskar et al., 2012). Most of these studies compared two or more management approaches to show how throughput can be maximized with proper choice of management approach under different circumstances. These studies suggest that the existing lane management approach will need modification with availability and increase of CAVs and CATs in traffic streams.

Lane management approach modification is likely to affect pavement design, construction, and life cycle cost analysis. Quantity and lane distribution of trucks significantly affect pavement design and subsequent performance. Higher amount of truck travel on the outside lane(s) generally leads to higher expenses for pavement construction and maintenance. Besides construction and maintenance costs, future fuel consumption costs are likely to change significantly.

Existing literature on lane management of regular vehicles, CAVs, and CATs focuses on the following key areas: capacity estimation, flow stability analysis, effect of platooning in mixed traffic environment, automated highway control algorithm, and congestion mitigation with CAVs. We did not find any study that looks into costs associated with possible lane management approaches to utilize benefits from connected and autonomous vehicles. Some light has been shed on fuel consumption of individual vehicle or a platoon but the overall area of agency or user cost is found unexplored. We have specially addressed the following questions in this study: (1) how does highway construction and rehabilitation cost change if truck platooning becomes a
commonplace reality on multilane highways, (2) to achieve promised fuel consumption savings with truck platooning, what should freeway lane management approach be and how much benefit can we expect with each choice of lane management approach, and (3) is fuel consumption reduction achieved by truck platooning large enough to cover the cost of tolled truck platooning highway lane(s).

The chapter starts with analysis of the effect of truck platooning on three major cost components of highway life cycle: construction, rehabilitation, and truck fuel consumption. Then the probable lane management approaches are introduced with a methodology of cost estimation. Finally, these approaches are numerically compared with costs of a hypothetical six-lane highway segment followed by discussion on future policy approaches for accommodating truck platooning.

3.3 Possible Lane Management Approaches

This section identifies possible lane management approaches for truck platooning on multilane freeways, ranging from prohibition of truck platooning to exclusively promoting it with additional platooning lane(s). These possible policy approaches can be divided into three broad categories: (1) limited or no truck platooning, (2) permitted truck platooning via existing highway lanes, and (3) over promoted truck platooning via exclusive and additional highway lanes. The first two categories consider truck platooning in mixed use lanes shared by trucks and passenger cars while the final category considers separate and additional lane(s) for truck platooning. Assumptions associated with each lane management approach are briefly discussed below.

3.3.1 Prohibitory

This represents a condition where trucks are not permitted to form or maintain platoons in any lane of the highway irrespective of technology evolution of vehicle connectivity and automation. This replicates the current situation where all the vehicles use the highway as a single
entity, maintaining enough time and space headway required for safe travel. This is considered as the base condition for our study where existing lane management approach, fuel consumption trend, pavement cost estimate, etc. are unchanged.

3.3.2 Conditional

Here, it is assumed that trucks are permitted to form and maintain platoon under certain conditions. Some examples of such conditions can be: permitting truck platoons at certain times of the day, fixing a maximum number of trucks that can join a platoon, allowing passenger cars to disrupt a platoon for lane changing. Within such a conditional environment trucks may be forced to form platoons in the outside lane only; also the platoons should be relatively shorter in length as the number of trucks in each platoon would be smaller. Depending on how much platooning can happen within such an approach, combined fuel consumption by all trucks within a reasonable period time, say a year, should still be less than the quantity consumed in the prohibitory approach.

3.3.3 One Lane

This approach explores the effect of permitting truck platooning on a designated lane other than the outside lane. Such an approach would make sure that regular movements of merging and diverging in the outside lane are not affected by platooning and vice versa. If there are at least three lanes in one direction of a highway segment, such an approach may allow faster movement of passenger cars via the third lane (other than the platooning lane and the outside lane) similar to the current trend. For highways with two lanes in one direction, passenger cars may not be able to gain such speed differential in the presence of truck platoons.

3.3.4 Two Lanes

For highways with three or more lanes in one direction, two inner lanes may be used for truck platooning. Similar to the example presented before, this may restrict faster movement of
passenger cars on these lanes when the two inside lanes are opened for platooning with three available lanes in one direction. But the passenger cars should be able to travel faster in additional lanes for highways with four or more lanes. This approach is not possible for highways with only two lanes in one direction.

3.3.5 All Lanes

Instead of being concentrated on one or two lanes, truck platoons can also take place based on varying traffic density and available space headway on any lane. This approach considered truck platoons on all highway lane(s). With significant advancement in vehicle to vehicle connectivity, trucks may be able to identify the most suitable lane for platooning at a certain time and then form platoon (or continue once formed) without having to make room for other vehicles to cut through. Interested readers can refer to Dao et al. (2008) and Dao et al. (2013) to understand how lane assignment can enable truck platoons to take place in any lane possible on a multilane highway. Such an approach can also handle longer platoons on the inside lane(s) of the highway and shorter platoons on the outside lane(s) of the highway.

3.3.6 Truck-only Lane

This approach considers an exclusive, additional highway lane built and operated only for truck platooning. This may ensure that the passenger cars would be able to change lanes according to requirement, without having to find space between the trucks that are part of a platoon. Also, passenger car platoons can take place in the car lanes and truck platoons can take place in the truck lane if lanes can be separated. In a later section, it is explored if such a lane could be financially feasible via tolls collected from the trucks.
3.4 Cost Estimation Methodology

3.4.1 Overall Approach to Life Cycle Cost (LCC) Estimation

Major components of Life Cycle Cost Analysis (LCCA) are initial construction, pavement preservation, rehabilitation, user cost, and environmental cost (Wall & Smith, 1998). Traditionally, for selecting pavement design, each of these components is estimated separately for possible design alternatives. The final LCC for each alternative is the sum of separately estimated cost components and is used for determination of the least LCC alternative. A similar approach is used here to determine the LCC trends for different possible highway lane management approaches. However, we do not expect all the components of LCC to change significantly for allowing truck platooning on the highways. The cost components not expected to change significantly for truck platooning across different management approaches are ignored in this study. Some of these components not expected to change for variation in lane management approaches are: pavement preservation cost, work zone user cost during maintenance and rehabilitation, crash cost, fuel consumption cost of the passenger cars, etc. It should be clarified that we expect many of the components to change dramatically due to large scale presence of connected and autonomous vehicles compared to current vehicle fleet. But this research focuses on the difference across lane management approaches when most or all vehicles are connected and autonomous, not the extent of change in LCC due to shift in vehicle technology. The three cost components expected to change for the study and given closer scrutiny are: construction of pavement, rehabilitation of pavement, and heavy vehicle fuel consumption.

A hypothetical highway segment, one kilometer in length, with three lanes in each direction is used for cost comparison across the lane management approaches. We assume that there are 1000 passenger cars per lane per hour on this highway segment and AADTT was 8000. We adopt
the volume of passenger cars to ensure that at least Level of Service (LoS) B (Highway Capacity Manual 2000) prevails in each lane. Underwood & Nagarajan, 2015 has enlisted AADTT in 2012 along major freight routes in the U.S. which ranges from 721 to 44,339. As the median AADTT in this list is 8104, we choose 8000 for our study. Underwood & Nagarajan, 2015 did not pair the AADTT figures with the total number of highway lanes but we assume that three lanes per direction is a reasonable quantity for a highway with an AADTT of 8000. Besides, three lanes per direction of the highway is the minimum to compare all the approaches presented in the previous section.

3.4.2 Construction Cost

Platooning of trucks in large quantities may lead to new approaches of lane management for the trucks. With changes in the lane management approach, the quantity of trucks on each lane will be different from the one observed now. This will change the pavement design and essentially, the construction cost for flexible pavement. It is possible that some of the parameters associated with pavement design besides the number of trucks will also change due to increased platooning (e.g. wheel wandering pattern, Chen et al., 2019). But this research only considers change in construction cost from increase or decrease in truck traffic on highway lane(s) caused by truck platooning.

First we designed a pavement section for each lane management approach and then estimated the cost required for each kilometer of a highway. For the design of flexible pavement, the AASHTO 1993 pavement design equation, recalled below, was used.

\[
\log_{10}(W_{18}) = Z_R \cdot S_0 + 9.36 \cdot \log_{10}(SN + 1) - 0.20 \cdot \frac{\log_{10}(\Delta PSI)}{0.40 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \cdot \log_{10} M_R - 8.07,
\]
and, \(SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 + \cdots,\)

where \(W_{18}\) is the predicted number of 80 KN (18,000 lb) Equivalent Single Axle Load (ESAL); \(Z_R\) is the standard normal deviate; \(S_0\) is the combined standard error of the traffic prediction and performance prediction; \(SN\) is the structural number indicative of the total pavement thickness required; \(\Delta PSI\) is the difference between initial design serviceability index and terminal design serviceability index; \(M_R\) is the subgrade resilient modulus in psi; \(a_i\) is the \(i^{th}\) layer coefficient; \(D_i\) is the \(i^{th}\) layer thickness in inches; and \(m_i\) is the \(i^{th}\) layer drainage coefficient.

Among many variables in this equation, it is assumed that all are fixed across lane management approaches except the design ESAL number. For multilane highways, the number of ESALs for each lane varies and the lane with the highest value is designated as the design lane. All other lanes are constructed similar to the ‘design lane’ even though the actual numbers of axle loads in these lanes are less than that in the design lane. Assumed design parameters in the AASHTO 1993 design equation are presented in Table 3.1.

Table 3.1 Material properties and other assumptions for estimation of asphalt concrete thickness

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>Basic Property/Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subgrade</strong></td>
<td>Resilient modulus,</td>
</tr>
<tr>
<td></td>
<td>(M_{Reff}: 103.42 \text{ MPa and } 41.37 \text{ MPa})</td>
</tr>
<tr>
<td></td>
<td>Thickness: 609.6 mm (24 inches)</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td>Resilient modulus: 193.05 MPa</td>
</tr>
<tr>
<td></td>
<td>Layer Coefficient: 0.15</td>
</tr>
<tr>
<td></td>
<td>Drainage coefficient: 1</td>
</tr>
<tr>
<td></td>
<td>Thickness: 254 mm (10 inches)</td>
</tr>
</tbody>
</table>
Table 3.1 (Continued)

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>Basic Property/Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asphalt Concrete</strong></td>
<td>Resilient modulus: 3447.38 MPa</td>
</tr>
<tr>
<td></td>
<td>Layer coefficient: 0.44</td>
</tr>
<tr>
<td></td>
<td>Drainage coefficient: 1</td>
</tr>
<tr>
<td><strong>Shared parameters</strong></td>
<td>( Z_R : -1.645 ) (95% reliability)</td>
</tr>
<tr>
<td></td>
<td>( S_0 : 0.5 )</td>
</tr>
<tr>
<td></td>
<td>( \Delta \text{PSI} : 1.5 )</td>
</tr>
<tr>
<td></td>
<td>Design life: 20 years</td>
</tr>
<tr>
<td></td>
<td>Annual traffic growth rate: 4%</td>
</tr>
<tr>
<td></td>
<td>Design speed 104.61 km/h (65 MPH)</td>
</tr>
<tr>
<td></td>
<td>Equivalency factor for conversion of AADTT to ESAL: 1.05 (FDOT, 2014)</td>
</tr>
</tbody>
</table>

Lane Distribution Factor (LDF) is the ratio of trucks in the design lane to the total number of trucks in that traffic direction. Higher value of LDF means almost all the trucks are concentrated on one lane, and a lower LDF indicates that the trucks are distributed across the available lanes. In order to take advantage of fuel savings, trucks may use the inside lanes more for uninterrupted movement of the platoons. Such movement would reduce the LDF for the outside lane. On the other hand, if the truck lane is separated from the car lanes to enhance platooning, the truck lane is likely to be used as the design lane.

For each lane management approach, the LDF value was assumed based on how platooning is permitted in some or all of the available lane(s). For the same highway and traffic condition, design ESAL was varied for each lane management approach depending on the possible range of LDF. Based on the usual range of LDF used for flexible pavement design as summarized by Hoque.
et al., 2018, the LDF values were assumed, as shown in Table 3.2. Note that the lane number in Table 3.2 starts from the median of the highway and increases towards the outside lane of the highway.

Table 3.2 Assumed LDF for different lane management approaches

<table>
<thead>
<tr>
<th>Management Approach</th>
<th>LDF in Lane 1</th>
<th>LDF in Lane 2</th>
<th>LDF in Lane 3</th>
<th>LDF in Lane 4</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prohibitory</td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
<td></td>
<td>Usual LDF for six-lane highways</td>
</tr>
<tr>
<td>Conditional</td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
<td></td>
<td>Same LDF as prohibitory approach</td>
</tr>
<tr>
<td>One lane</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td></td>
<td>Lane 2 is truck platooning lane</td>
</tr>
<tr>
<td>Two lanes</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td></td>
<td>Lane 1 and lane 2 are truck platooning lanes</td>
</tr>
<tr>
<td>All lanes</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Truck-only</td>
<td>0.7</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>Lane 1 is truck only lane</td>
</tr>
</tbody>
</table>

For simplicity of analysis, it is assumed that the pavement consists of three layers: subgrade, base, and asphalt concrete. The roadway construction cost was found as a function of asphalt concrete thickness under different lane management approaches.

Construction cost (CC) for L number of lanes can be expressed as:

\[ CC = \sum_{i=1}^{L} (AC \times ACR + B \times BR + EW \times EWR), \]
where AC is the thickness of asphalt concrete layer; ACR is the cost per unit layer thickness of asphalt concrete including material and placement of material; B is the thickness of base layer; BR is the rate of base layer including material and placement of material; EW is the thickness of sub-grade; and EWR is the rate of sub-grade layer including material and placement of material. AC, B, and EW can be estimated from the AASHTO 1993 design equation or Mechanistic Empirical Pavement Design Guide (MEPDG). We have used the first one. Cost of asphalt concrete, base material and sub-grade were from average FDOT bid rates in 2017 (FDOT, 2017).

3.4.3 Rehabilitation Cost

Similar to the case of construction cost, change in rehabilitation cost due to truck platooning can be estimated from the volume of truck traffic on each highway lane. However, unlike the case for construction cost, rehabilitation cost estimation for multilane highways requires the volume of truck traffic on each lane instead of the number of trucks on the design lane only. The truck traffic volume on each lane during the design life was found from the assumption made regarding how trucks would use lanes under each approach shown in Table 3.2.

With the fraction of AADTT known for each lane in the first year, the yearly cumulative number of trucks on each lane was generated with the assumption of 4% yearly growth during the design life of 20 years. This cumulative volume of traffic on each lane was used in predicting pavement condition at the end of each year from simplified pavement performance models (Lee et al., 1993). These models express pavement condition in terms of Present Serviceability Index (PSI) at a certain year. We assumed 4.5 as the initial PSI when pavement is constructed or just rehabilitated and 3.0 is the intervention PSI when the next rehabilitation would be conducted. For each lane, PSI prediction for each lane in every year can be made according to simplified pavement performance models from following variables: thickness of pavement layers, pavement age, initial
PSI, climate condition, cumulative ESAL carried in the year of prediction. In this study, the pavement layer thicknesses are presented in Section 3.2; design life was assumed to be 20 years and so pavement age was varied from 1 to 20 years; climate condition was assumed as non-rain and non-frost. Time of intervention or rehabilitation year was when the initial PSI would drop from 4.5 to 3.0. However, some lanes with a lower volume of truck traffic did not reach PSI 3.0 during the 20 years and were rehabilitated at Year 16 with a minimum resurfacing of 0.5 inches. For the remaining lanes under different lane management approaches, resurfacing depth was determined according to Florida Department of Transportation (FDOT) flexible pavement design manual (FDOT, 2018). Depth of milling was assumed to be 0.5 inches more than the resurfacing depth. In order to calculate the rehabilitation cost, milling rate was taken from the statewide average in 2016 (FDOT, 2016) and rate of asphalt concrete was taken from average FDOT bid rates in 2017 (FDOT, 2017). Rehabilitation costs found in particular years were converted to the Net Present Value (NPV) with an assumed discount rate of 3%. Salvage value was deducted from the rehabilitation cost in case 10-year design period of rehabilitation was not met during the 20-year analysis period.

3.4.4 Fuel Consumption Cost

Fuel consumption estimate of vehicles on a highway can be achieved by applying a fuel consumption model to the vehicle trajectory data on that segment at a certain time period. Additionally, the platoon sizes and strengths that are formed in a certain segment of a highway with similar traffic and driving conditions may not be exactly the same in any two different instances; there are too many random factors that can affect the number of vehicles that would form platoons. To overcome these challenges, we proposed a methodology to generate vehicle trajectories that can capture randomness in the process of platoon formation. This section describes
the derivation of the fuel consumption cost. To determine this cost, a simulation model was
developed to derive the vehicle trajectories. With these microscopic trajectories, the fuel
consumption cost can be estimated using the existing fuel consumption models in the literature.

The simulation model developed in this study includes four vehicle types: 1) human-driven
light vehicles (HV), 2) connected automated light vehicles (CAV), 3) human-driven trucks (HT),
and 4) connected automated trucks (CAT). The fuel consumption cost analysis includes three steps.
In the first step, the traffic boundary conditions are determined. These conditions specify the
vehicle types and their corresponding arrival times to the simulation zone. These conditions are
determined using an analytical model. Given the boundary conditions, the vehicle trajectories are
simulated in the second step. Taking the trajectories as inputs, the fuel consumption cost is
estimated in the third step.

Considering the four vehicle types, the spatial distribution of the mixed traffic along a
highway segment will have a complex structure that includes 16 different types of distributions for
a general pair of consecutive vehicles (e.g., two vehicles of type 1 following each other, vehicle
type 1 following type 2, vehicle type 2 following type 1, etc.). Further, the distributions of these
pairs depend on a few factors including lane management strategies, percentages of all four vehicle
types in traffic, and the intensities of platooning technologies of connected automated vehicles.
Moreover, the time headway between each of the 16 vehicle pair types is not a fixed value. Instead,
it is a stochastic value, which follows a probabilistic distribution. These complexities make the
traffic boundary condition modeling a challenging task. To overcome these issues, a Markov-chain
model, inspired by Ghiasi et al., (2017), is developed to determine the simulation boundary
conditions with respect to the lane management scenario, percentages of vehicle types, platooning
intensities, and stochastic distributions of time headways. Given these boundary conditions,
vehicle trajectories are then simulated over a certain segment of a highway using the IDM car-following model (Liu et al., 2016). With these trajectories, the total fuel consumption of traffic and the corresponding cost can be determined with the Virginia Tech Comprehensive Power-based Fuel consumption Modeling (VT-CPFM) framework (Wang and Rakha, 2017). Details of the problem setting and the three steps to fuel consumption cost estimation are described as follows.

3.4.4.1 Simulation Settings

We consider a segment of a highway with a length of G and L number of lanes that are indexed as \( l \in \mathcal{L} := \{1, 2, ..., L\} \). A stream of \( N_l \) vehicles is assumed to enter lane \( l \) of the highway segment that are indexed as \( n \in \mathcal{N}_l := \{1, 2, ..., N_l\} \). In this notation, vehicles are indexed from downstream to upstream, such that vehicle \( n + 1 \) follows vehicle \( n \), \( \forall n \in \mathcal{N}_l/\{N_l\}, l \in \mathcal{L} \). Let \( \mathcal{Y} := \{1,2,3,4\} \) denote the set of vehicle types, whose elements represent HV, CAV, HT, and CAT, respectively. Further, let \( Y_{lny}, l \in \mathcal{L}, n \in \mathcal{N}, y \in \mathcal{Y} := \{1,2,3,4\} \) defines the vehicle type index such that \( Y_{lny} = 1 \) if the type of vehicle \( n \) on lane \( l \) is \( y \), 0 otherwise. Then, let \( P_{ly} \) denote the percentage of vehicles of type \( y \in \mathcal{Y} \) among all \( N_l \) vehicles on lane \( l \), which is formulated as the expected value among all \( N_l \) vehicles on lane \( l \):

\[
P_{ly} := \mathbb{E}\left( \frac{\sum_{n \in \mathcal{N}_l} Y_{lny}}{N_l} \right), \forall l \in \mathcal{L}.
\]

Further, we let \( h_{ln} \) define the boundary time headway between vehicle \( n \) and \( n + 1 \) at lane \( l \), \( \forall n \in \mathcal{N}_l/\{N_l\}, l \in \mathcal{L} \).

Now, let \( O \in [0,1] \) denote the platooning strength of connected automated trucks (vehicle type 4). This parameter basically determines the likelihood of the following vehicle to be type 4 given a preceding vehicle type for each pair of vehicles. On an extreme case, if \( O \) is set to its maximum value, then given that the preceding vehicle type is 4, the type of the following vehicle...
is also 4. Otherwise, if the preceding vehicle type is not 4, then the vehicle type of the following vehicle is not 4 either. This means that all trucks are formed into one single platoon. Note that this extreme case will not happen in real-world traffic, and is just defined for the completeness of the analysis. On the other side of the spectrum, if $O$ is set to its minimum value, the vehicles are randomly distributed along the highway and thus the type of each vehicle is independent of the preceding one. Figure 3.1 illustrates the two extreme cases, followed by an intermediate case. The first case in Figure 3.1 (a) shows a condition where the platooning strength is minimum and all the four types of vehicles are separated from each other. In Figure 3.1 (b), all the connected autonomous vehicles are clustered together to form platoons with the highest platooning strength. The final illustration in Figure 3.1 (c) shows an intermediate scenario when the CATs form two separate platoons in between HTs.

![Figure 3.1 Vehicle distribution possibilities for truck platoon formation](image)

Figure 3.1 Vehicle distribution possibilities for truck platoon formation
3.4.4.2 Boundary Conditions

The simulation boundary conditions depend on a number of factors including the percentage of vehicle types on each lane of the highway (i.e., $P_{ly}$), the platooning strength of connected automated trucks (i.e., $O$), and boundary time headway of vehicles (i.e., $h_{tn}$). To integrate all these factors into a single analytical model, a discrete Markov-chain model is developed to specify the vehicle types as the simulation boundary condition. In this model, $\mathcal{Y}$ can be considered as the state space, and the initial state at each lane $l$ can be defined as

$$\pi_l := [P_{l1}, P_{l2}, P_{l3}, P_{l4}], \forall l \in \mathcal{L}.$$ 

Then the transition matrix is defined as

$$T_l := \begin{bmatrix} t^l_{11} & t^l_{12} & t^l_{13} & t^l_{14} \\ t^l_{21} & t^l_{22} & t^l_{23} & t^l_{24} \\ t^l_{31} & t^l_{32} & t^l_{33} & t^l_{34} \\ t^l_{41} & t^l_{42} & t^l_{43} & t^l_{44} \end{bmatrix}, \forall l \in \mathcal{L},$$

where $t^l_{xz}$ denote the probability that a type-$x$ vehicle is followed by a type-$z$ vehicle at lane $l$, i.e.,

$$t^l_{xz} := \Pr(Y_{l(n+1)z} = 1|Y_{lnx} = 1), \forall n \in \mathcal{N}_l/\{N_l\}, l \in \mathcal{L}, x, z \in \mathcal{Y}$$

that is reformulated as a function of $P_{ly}$ and $O$ as follows.

$$t^l_{sr} := \frac{P_{lr}}{1-P_{lr}}(1 - P_{lr}(1 - O)), s, r \in \{1,2,3\}, \forall l \in \mathcal{L},$$

$$t^l_{4r} := P_{lr}(1 - O), r \in \{1,2,3\}, \forall l \in \mathcal{L},$$

$$t^l_{s4} := P_{l4}(1 - O), s \in \{1,2,3\}, \forall l \in \mathcal{L},$$

$$t^l_{44} := 1 - (1 - P_{l4})(1 - O), \forall l \in \mathcal{L}.$$ 

With initial state $\pi_l$ and transition matrix $T_l$, the Markov-chain model can be defined for each lane, denoted by $M_l(\pi_l, T_l), \forall l \in \mathcal{L}$. This Markov-chain model takes $P_{ly}$ and $O$ parameters as inputs. Parameter $O$ is designed such that it increases from 0 to 1 as the platooning intensity
increases from minimum (independent platooning) to maximum (perfect platooning). The extreme platooning cases are defined according to the probabilities of the types of two general consecutive vehicles. To link this parameter value to the platooning sizes, Figure 3.2 plots different $O$ values against different vehicle percentages.

![Platoon Size](image)

Figure 3.2 Platoon size, platoon strength and truck percentage

Note that when the real-world traffic data is available, $P_{ly}$ and $O$ parameters can be easily calibrated, which is beyond the scope of this research. Interested readers can refer to Husain et al., 2019 for parameter calibration procedure. Finally, $h_{ln}$ values are determined according to the traffic demand at the entrance of the highway segment as

$$ h_{ln} := h_{l(n-1)} + \max(h_{\min}^{y,y'}, v_{ln}^y), \forall n \in \mathcal{N}/\{N_l\}, l \in \mathcal{L}, y \in \mathcal{Y}, $$

where $h_{\min}^{y,y'}$ is the minimum possible time headway of vehicle type $y$ followed by vehicle type $y', (y, y' \in \mathcal{Y})$ that is basically the $(y, y')$ element of the $h_{\min}$ matrix. The $h_{\min}$ (in meter) matrix values are derived from the corresponding IDM car-following model parameters presented in the following subsection and are presented as follows.
\[
\begin{bmatrix}
1.40 & 1.40 & 2.05 & 2.05 \\
1.40 & 1.40 & 2.05 & 2.05 \\
1.95 & 1.95 & 2.70 & 2.70 \\
1.95 & 1.95 & 2.70 & 2.70 \\
\end{bmatrix}
\]

\( h_{\min} \)

\[ \vartheta_{ln}^y \] is a normally-distributed time headway defined as

\[ \vartheta_{ln}^y \sim \mathcal{N}(\overline{h}_{ln}, \sigma_{ln}), \forall n \in N_i/\{N_i\}, l \in L, y \in \mathcal{Y}, \]

where \( \overline{h}_{ln} \) is the expected value of the time headway of vehicle \( n \) following \( n + 1 \) at lane \( l \) (i.e., the inverse of average traffic flow) and \( \sigma_{ln} \) is the time headway standard deviation that is defined as \( \sigma_{ln} \equiv 0.2\overline{h}_{ln} \) in this study.

### 3.4.4.3 Car Following Model

The previous subsection provided the simulation boundary conditions through a Markov-chain model that determines the vehicle spatial distribution at each lane along the highway. We run the Markov-chain model for a predetermined number of vehicles. With the boundary conditions for a stream of vehicles, the vehicle trajectories are simulated using the IDM car-following model. This car-following model is formulated as

\[
a_{ln} = \overline{a}_{ln} \left( 1 - \left( \frac{v_{ln}}{\bar{v}} \right)^{\eta} - \left( \frac{s_{ln}}{s_{ln}^0} \right)^2 \right), \forall n \in N_i, l \in L,
\]

\[
s^* = s_{ln}^0 - s_{ln}^y + \max \left( 0, v_{ln} T_{ln} + \frac{v_{ln} \Delta v_{ln}}{2\sqrt{\overline{a}_{ln} b_{ln}}} \right), \forall n \in N_i, l \in L,
\]

where \( v_{ln} \) and \( a_{ln} \) are the vehicle speed and acceleration, respectively, \( \overline{a}_{ln} \) and \( b_{ln} \) are the maximum acceleration and comfortable deceleration, respectively, \( s^* \) is the actual gap, \( s_{ln}^0 \) is the traffic jam spacing, \( s_{ln}^* \) is the desired space gap, \( s_{ln}^y \) is the vehicle length, \( T_{ln} \) is the time gap, \( \Delta v_{ln} \) is the speed difference between the preceding and the current vehicle (\( \Delta v_{ln} := v_{l(n+1)} - v_{ln} \), \( \forall n \in N_i/\{N_i\}, l \in L \)), and \( \eta \) is the acceleration exponent. The model parameters for regular and heavy
vehicles are taken from Liu et al., 2016. However the maximum speeds of car and truck following were updated accordingly: maximum speed of regular and CAVs 30 m/s, maximum speed of HTs 25 m/s, and maximum speed of CATs 24 m/s, maximum speed for the trucks in a truck-only lane is 23 m/s. Acceleration exponent is assumed to be 4 (Treiber et al., 2000), and truck platooning gap is 10 m. Reaction times are 1.4 s for HVs, 1.2 s for HTs, and 0.3 s for both CAVs and CATs. Other model parameters can be found in Table 3.3.

Table 3.3 Car following model parameters (Liu et al., 2016)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Car following</th>
<th>Car following</th>
<th>Truck following</th>
<th>Truck following</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum acceleration, $\bar{a}_{ln}$ in m/s$^2$</td>
<td>1.01</td>
<td>1.03</td>
<td>0.78</td>
<td>0.74</td>
</tr>
<tr>
<td>Maximum speed, $\bar{v}$ in m/s</td>
<td>30</td>
<td>30</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>Traffic jam spacing, $s_{ln}^0$ in m</td>
<td>0.85</td>
<td>1.35</td>
<td>1.11</td>
<td>1.53</td>
</tr>
<tr>
<td>Desired space gap, $s_{ln}^v$ in m</td>
<td>0.19</td>
<td>0.27</td>
<td>0.12</td>
<td>0.36</td>
</tr>
<tr>
<td>Safe time headway, $T_{ln}$ in s</td>
<td>1.2</td>
<td>1.4</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Comfortable deceleration, $b_{ln}$ in m/s$^2$</td>
<td>2.26</td>
<td>2.12</td>
<td>1.7</td>
<td>1.61</td>
</tr>
</tbody>
</table>
Using this car-following model, vehicle trajectories can be obtained for the entire length of highway segment G. With vehicle trajectory data, one can calculate the fuel consumption of the considered vehicle stream by applying a fuel consumption model, which is discussed in the next sub-section. For simplicity, effects of vehicle lane changing maneuvers are ignored in this analysis. This exclusion may have limited impacts on the fuel consumption cost for two main reasons. First, the effects of lane changing maneuvers on the basic segments of the highway (especially with managed lane) on the fuel consumption might be marginal. Second, the excessive fuel consumptions caused by lane changes might be similar across different lane management scenarios, and thus these excessive costs can be canceled in cross-comparing the scenarios.

3.4.4.4 Fuel Consumption Model

This subsection presents the fuel consumption cost model. With the obtained vehicle trajectory data, we can apply a microscopic fuel consumption model to the entire stream of traffic on all lanes. In this paper, we consider the VT-CPFM fuel consumption function (Wang & Rakha, 2017) that is a simple framework expressing fuel consumption as a second order polynomial function of vehicle power. This model first finds the resistance force being applied on the vehicle, which is formulated as

\[
R(t) = \frac{R(t) + (1 + \lambda + 0.0025\xi v(t)^2)m a(t)}{3600\eta} v(t),
\]

where \( P(t) \) is the vehicle power; \( \lambda \) is the mass factor accounting for rotational masses; \( \xi \) is the gear ratio and assumed to be zero in this study due to the lack of engine gear data; \( a(t) \) is the vehicle instantaneous acceleration; and \( \eta \) is the driveline efficiency.

The final model for estimation of fuel consumptions is expressed as

\[
FC(t) = \begin{cases} 
\alpha_0 + \alpha_1 + \alpha_2 P(t)^2, & \forall P(t) \geq 0 \\
\alpha_0, & \forall P(t) < 0
\end{cases}
\]
where FC(t) is the fuel consumption rate at instant t (in liter per seconds); $\alpha_0$, $\alpha_1$ and $\alpha_2$ are vehicle specific model coefficients. For this study we assumed that the heavy vehicle is a Freightliner truck, model FLD 120, make 2001 according to Wang & Rakha, 2017 and have used the calibrated parameters for such a truck. These coefficients and other parameter values mentioned above for estimation of fuel consumption in this study are summarized in Table 3.4.

Table 3.4 VT-CPFM model parameters and assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumed value</th>
<th>Literature reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>20 m</td>
<td>Assumed</td>
</tr>
<tr>
<td>Truck mass</td>
<td>30,000 kg</td>
<td>Assumed</td>
</tr>
<tr>
<td>Air density</td>
<td>1.2256 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Frontal area</td>
<td>10 m$^2$</td>
<td></td>
</tr>
<tr>
<td>$C_r$</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>$c_1$</td>
<td>0.0328</td>
<td></td>
</tr>
<tr>
<td>$c_2$</td>
<td>4.575</td>
<td>Wang &amp; Rakha, 2017</td>
</tr>
<tr>
<td>Mass factor</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Gear ratio</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Driveline efficiency</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>2.16E-03</td>
<td></td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>7.98E-05</td>
<td></td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>1E10-8</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.5 shows that there is no consensus on the quantity of fuel consumption saving of the trucks that travel closely as a platoon. The range of fuel consumption savings varies from 2% to 25%.
We assumed that the leading truck in a platoon would save 5% fuel compared to a condition when the truck is travelling along and similarly, 10% saving for any number of trailing trucks that are part of a platoon. CATs that are not part of the platoon do not save fuel for this study, consuming the same fuel as an HT.

Table 3.5 Fuel consumption savings for the trucks in a platoon

<table>
<thead>
<tr>
<th>Authors, publication year</th>
<th>Lead vehicle fuel saving (%)</th>
<th>Middle vehicle fuel saving</th>
<th>Trailing vehicle fuel saving (%)</th>
<th>Source of findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Alam et al., 2010</td>
<td>none</td>
<td>N/A</td>
<td>4.7 - 7.7</td>
<td>Field test</td>
</tr>
<tr>
<td>Tsugawa et al., 2016</td>
<td>0 - 9</td>
<td>13 – 23</td>
<td>15 - 25</td>
<td>Experiment, simulation</td>
</tr>
<tr>
<td>Browand et al., 2004</td>
<td>5 - 10</td>
<td>N/A</td>
<td>10 - 12</td>
<td>Field test</td>
</tr>
<tr>
<td>Lu &amp; Shladover, 2011</td>
<td>4.3</td>
<td>10</td>
<td>14</td>
<td>Field test</td>
</tr>
<tr>
<td>Lyamin et al., 2016</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>Simulation</td>
</tr>
<tr>
<td>Tsugawa et al., 2011</td>
<td>7.5</td>
<td>16</td>
<td>16</td>
<td>Experiment, simulation</td>
</tr>
<tr>
<td>Lammert et al., 2014</td>
<td>2.7 – 5.3</td>
<td>N/A</td>
<td>2.8 – 9.7</td>
<td>Field test, simulation</td>
</tr>
<tr>
<td>Davila et al., 2013</td>
<td>1 - 7</td>
<td>N/A</td>
<td>8 - 16</td>
<td>Field test, simulation</td>
</tr>
<tr>
<td>Jin et al., 2017</td>
<td>0</td>
<td>9</td>
<td>20</td>
<td>Simulation</td>
</tr>
</tbody>
</table>

3.4.4.5 Fuel Consumption Ranges

We simulated the movement of cars and trucks on the three lanes in one direction of a highway for ten minutes. This produced the trajectory data for the vehicles and allowed us to find fuel consumption estimate for different lane management approaches. Within each approach, we repeated the simulation process for 25 times with one set of platooning strength (Table 3.6).
Another 25 repetitions were made with the second set of platooning strength. A trial run of more than 25 times may produce less variation between different set of trials but we chose 25 as a reasonable for the following analysis. Two probable set of fuel consumption quantities, one with low platooning strength inputs, and another with high platooning strength inputs were thus generated. This was done in order to demonstrate a possible range of fuel consumption benefit for different approaches. It needs to be mentioned that the maximum and minimum fuel consumption quantities found from this process are not absolute minimums and maximums.

Table 3.6 Platooning strength and platoon size variation

<table>
<thead>
<tr>
<th>Management approach</th>
<th>Platooning Strength (Low/High)</th>
<th>Maximum number of trucks in a platoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lane 1</td>
<td>Lane 2</td>
</tr>
<tr>
<td>Conditional</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>One lane</td>
<td>(0.4/0.8)</td>
<td>0</td>
</tr>
<tr>
<td>Two lanes</td>
<td>(0.4/0.7)</td>
<td>(0.4/0.7)</td>
</tr>
<tr>
<td>All lanes</td>
<td>(0.4/0.7)</td>
<td>(0.4/0.7)</td>
</tr>
<tr>
<td>Truck only lane</td>
<td>(0.5/0.8)</td>
<td>0</td>
</tr>
</tbody>
</table>

3.4.4.6 Fuel Consumption Cost and Saving for One Year

Fuel consumption cost for one year, found from multiplying the average fuel consumption quantity for each approach with the AADTT and the number of days per year with an assumed price of each gallon of diesel ($3.18 USD). For the truck-only lanes approach, the cost was found in two groups. We assume that 70% of the trucks have used the designated truck lane (Lane 1) and have consumed lower quantity of fuel as they participate in platoons. The second group of trucks (30% of the AADTT) have not used the platooning lane and have consumed the same quantity of
fuel as we found in the prohibitory approach. Finally, the savings in fuel consumption cost for each approach was found by subtracting the yearly fuel consumption for the first year of that approach from the cost of fuel consumption of the base (prohibitory) approach. Similarly, fuel consumption for future years can be found with the consideration of traffic growth and change in fuel price over the years.

3.5 Cost Trends - Results

Allowing truck platooning generally reduces construction cost of highways for unit length of highway if additional lane is not added to the highway for truck platooning. This happens because the alternative lane management approaches require more trucks to use the inside lane(s) of the highway segment. The alternative lane management approaches generally ensure that the frequency of trucks joining a platoon is higher and the platoons have more trucks on average compared to the no-platoon approach. As the trucks use the inside lane(s) more frequently due to platooning, the number of trucks on the design lane and the construction cost estimate of the highway segment decreases. But the addition of a separate truck platoon lane increases the construction cost per unit length of highway.

Rehabilitation cost increases for the approaches that promote truck platooning. Primarily, with more use of inside lanes by truck platoons, the number of trucks on the design lane decreases and the pavement structure is designed for that smaller quantity of trucks compared to an approach where most trucks are on the design lane. The resulting pavement structure is less robust. The second reason is that the truck traffic volume on each inside lane is assumed to be higher for truck platooning during the design life of pavement. In combination, distributing trucks from the outside lane(s) to the inside lanes reduces construction cost but increases rehabilitation cost. These two
conflicting cost trends ensures that the agency cost (i.e., construction and rehabilitation cost) per unit length of highway does not change much when there is no additional lane for truck platooning.

Fuel consumption quantity of the trucks, as expected, decreases for all the approaches compared to the prohibitory approach (no-platoon). Figure 3.3 shows how fuel consumption varies for different approaches of lane management of the example highway considered for the study. For every approach, two sets of fuel consumption quantities are presented here. The first set represents average fuel consumption of all the trucks when platooning strength is low and the second set gives fuel consumption with high platooning strength. So the second set gives a smaller prediction of average fuel consumption within the same approach. Across the approaches, fuel consumption continues to decrease as more lanes are opened for truck platooning. But the decrease in fuel consumption for allowing truck platooning in two lanes is not much less compared to the fuel consumption for truck platoon in one designated lane. Opening all the lanes makes the decrease in fuel consumption a sizable one. But adding a dedicated lane for platooning of trucks reduces fuel consumption quantity further.

![Figure 3.3 Fuel consumption of the trucks for different lane management approaches](image-url)
Table 4.1 shows that highway agencies can reduce cost by allowing truck platooning. User cost (due to fuel consumption) also decreases for the trucks that take advantage of platooning. The table also shows that the reduction in fuel consumption cost in one year for the truck-only lanes approach is significantly higher than the cost incurred for an additional lane. Without an additional lane, a highest saving of USD 88,000 per year can be achieved via the “all lanes” approach. By adding a lane for truck platooning, an additional USD 41,000 per unit length may be saved. The difference in agency cost between these two approaches is USD 36,000 and can be regarded as the additional yearly cost of truck-only lane. This cost difference can potentially be recovered from the saving of fuel consumption by the trucks that would use the extra lane. Additionally, the truck-only lane approach reduces the highway rehabilitation cost for unit length of highway segment as most trucks are channeled to the platooning lane resulting in reduced damage of the car lanes and subsequent rehabilitation cost.

Table 3.7 EUAC costs (in thousands, USD) for construction, rehabilitation, and truck fuel consumption cost per year on one kilometer of highway for different lane management approaches

<table>
<thead>
<tr>
<th>Management approach</th>
<th>EUAC Construction (USD, 1000)</th>
<th>EUAC Rehabilitation (USD, 1000)</th>
<th>EUAC Agency (USD, 1000)</th>
<th>Fuel Consumption (USD, 1000)</th>
<th>Fuel Cost Saving (USD, 1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
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<td>93</td>
<td>8</td>
<td>102</td>
<td></td>
<td>1354</td>
</tr>
<tr>
<td>One lane</td>
<td>86</td>
<td>11</td>
<td>97</td>
<td></td>
<td>1346</td>
</tr>
<tr>
<td>Two lanes</td>
<td>82</td>
<td>15</td>
<td>97</td>
<td></td>
<td>1331</td>
</tr>
<tr>
<td>All lanes</td>
<td>82</td>
<td>15</td>
<td>97</td>
<td></td>
<td>1301</td>
</tr>
<tr>
<td>Truck-only lane</td>
<td>124</td>
<td>9</td>
<td>133</td>
<td></td>
<td>1259</td>
</tr>
</tbody>
</table>
3.6 Conclusions and Remarks

This chapter analyzed different highway lane management approaches that can accommodate truck platoons within the vehicle stream. The analysis includes three cost components: highway construction, rehabilitation, and fuel consumption for the trucks. There are available models to rely on for highway construction and rehabilitation cost estimation, but not as many for the fuel consumption cost when the travelling vehicles can form platoons while using a highway segment. This study proposes a Markov-chain model to simulate heterogeneous traffic with probability of truck platoons to take place with varying platoon intensity and percentage.

We found that truck platooning on a multilane highway can reduce both the agency cost and fuel consumption cost. Addition of a truck-only lane for platoons can increase agency cost but the drop in fuel consumption cost is large enough to support the cost of an additional lane. These findings are achieved from simulation of vehicle movement on a six-lane highway.

As a minimum, highway agencies can allow truck platooning on the outside lane with a maximum platoon size of two trucks. Keeping the maximum size to two trucks can ensure that the merging and diverging vehicles can still use the outside lane without having to disrupt the platoons or to wait for the platoon to pass. This may ensure that some of the trucks can take advantage of platooning while the highway operation is not altered much. However, the traffic conditions may not allow truck platooning on the outside lane without disrupting regular movement of merging and diverging vehicles on the busy routes.

Designating one of the inside lanes for truck platooning may ensure that the truck platoons do not interfere with regular vehicle movement in the outside lane. Currently the inside lanes are more used by faster passenger cars. It needs to be carefully considered if allowing truck platooning in such a fast lane will hinder the passenger cars from gaining the speed advantage like before and
if the hindrance has any safety implication. Distributing truck platoons on the two inside lanes 
(with three available per direction) can ensure that the truck platoons take full advantage of the 
inside lanes but are not too long to hinder regular vehicle movement. Further distribution of truck 
platoons can be achieved by allowing platoons on all the lanes. With availability of vehicle to 
vehicle and vehicle to infrastructure connectivity, trucks may be able to identify the lane most 
suitable for platooning at a certain time and choose that particular lane without affecting other 
vehicles on the highway. Allowing truck platoons in one, two or three lanes can also be a dynamic 
decision, based on the traffic condition. For example, only limited platooning can be allowed in 
one of the inside lanes during a busy period and other lanes can be opened during off-peak hour 
depending on incoming traffic volume.

Addition of a truck platoon lane to the highway segment allows longer truck platoons to 
take place and also ensures that the platoons do not hinder regular operation of the passenger cars. 
Cost of adding a dedicated lane may require toll collection from the trucks that would use the 
dedicated lane. Highway agencies can conduct survey to find out if the trucks are willing to share 
part of the fuel consumption saving as tolls and if the tolls would be enough to fund the additional 
lane. Inclusion of right-of-way cost into the construction cost of the additional truck lane should 
be considered carefully specially in urban areas. If the right of way is limited and the additional 
lane would require a highway agency to purchase land for the truck platooning lane, careful 
consideration should be given about financial viability of additional truck platooning lane.

This study only considered platooning of trucks and subsequent fuel consumption benefits. 
Similar methodology may be applied to simulate platooning of passenger cars. For trucks, we 
focused on a specific truck volume and highway lane configuration. Future studies can be
conducted for different volumes and lane configurations to find out how the highway cost analysis will change in general due to platooning of vehicles.
Chapter 4: Conclusions and Direction for Future Work

4.1 Summary and Conclusions

This research investigates the impact of highway lane management policy on the cost of flexible pavement for two types of vehicles: existing vehicle fleet driven by humans and connected and autonomous vehicles. The major cost components considered for the existing vehicles are construction/reconstruction cost and rehabilitation cost during the life cycle of pavement. For connected and autonomous vehicles, the policy options were weighed for the fuel consumption cost of trucks besides the construction/reconstruction and rehabilitation cost.

Current highway lane management policy, on most freight routes, imposes lane restriction on the trucks using multilane highway. Also the trucks generally use the outside lanes even when there is no restriction in place as they need more space to accelerate or decelerate. This practice has considerable implication on highway construction/reconstruction cost. As the pavement design is dependent on the quantity of trucks on the design lane (the outside lane in most cases), restriction on trucks to stay on the outside lanes increases the construction/reconstruction cost estimate. The effect is compounded in either case of increased passenger car volume or increased truck volume. With increased passenger car volume, more lanes would be required adding to the per mile construction/reconstruction cost; with increased truck volume, the design lane would require more robust structural capacity to withstand the applied load.

It was investigated if there were alternative approaches to current truck lane restriction that would reduce highway cost. We found that distributing trucks among the available lanes reduces
highway construction/reconstruction cost when all else are same. Other possible alternatives that have been analyzed are: designing and constructing each lanes individually as per the quantity of trucks on each lane and adding separate truck-only lanes to the system. Each of these alternatives reduces construction/reconstruction cost to some extent. Relative degree of cost saving would depend on the specific site condition and traffic volume. However, rehabilitation cost increases with all the alternatives. The combined LCC is determined by the construction/reconstruction cost as the rehabilitation cost is a very small fraction of the former cost component. Highway agencies may consider any of these alternative approaches to reduce LCC. Addition of truck-only lanes may require extra right of way for the highway. This additional cost of travel lanes was considered in this research and does not change the cost trend for the example considered for analysis.

Possible range of lane management for connected and autonomous vehicles needs a thorough scrutiny as the benefits of platooning largely depends on the choice of lane management policy. Some of these possible approaches were considered (Chapter 3) in this research assuming ubiquitous presence of connected an autonomous vehicles on the highways. The range of lane management approaches were considered to have no truck platooning, limited amount of truck platooning, moderate truck platooning, and high intensity truck platooning via separate truck-only, platooning lanes. Among many possible cost implications of truck platooning, only construction/reconstruction, rehabilitation, and fuel consumption cost implications were investigated. Estimate of possible fuel consumption requires simulation of heterogeneous vehicle (passenger cars and trucks) movement. A Markov-chain model was proposed to simulate heterogeneous traffic movement with different probable truck platoon formations based on available space for the truck platoons.
Lane management approaches that allow higher degree of truck platooning were found to have twofold benefits: reduction of construction/reconstruction cost and reduction of fuel consumption cost. Rehabilitation cost increases for most of the approaches considered. Overall, the agency cost trend is dictated by the construction/reconstruction cost quantity and showed decrease for the possible lane management approaches. Addition of truck-only lane to promote platooning increased construction/reconstruction cost of unit length highway as it needs additional lane but reduced the truck fuel consumption cost by a larger margin compared to the approaches that allowed truck platooning via mixed lanes. This reduction of fuel consumption cost was found to be larger than the cost of an additional truck-only lane for the example considered here. Such savings from truck platooning may be utilized in the freight routes to plan and build tolled truck platoon lanes.

This research showed that highway lane management approach already has considerable cost impact for flexible pavement and is likely to have higher impact with the future vehicles capable of platooning. The highway agencies have an opportunity to explore the potential cost trends and reduce future highway costs. They also may consider truck-only lanes approach for the routes with sizable truck traffic volumes.

4.2 Research Contributions

This research highlights the cost side of highway lane management when traditionally lane management is viewed from the perspective of highway capacity and throughput. This research shows that there is cost inefficiency involved in the current manner of lane management. Highway agencies in most U.S. states have gaps between overall fund requirement for highway maintenance and improvement and the actual availability every year. One of the ways to reduce such gaps can be lowering highway construction/reconstruction cost. No matter how slow the growth of highway
system may be, most highway agencies are adding highway lane miles to the system and will continue to do so in the near future. More commonly, the existing lane miles within the aging highway system reach terminal pavement condition at some point of their life cycle and require reconstruction. With traditional approach of highway lane management and pavement design, new construction or reconstruction would be quite costly. This research shows that agencies can adopt more efficient ways to manage highway lanes for heterogeneous vehicles and also can innovate with pavement design to reduce construction/reconstruction cost.

The concept of truck-only lanes for highways has been analyzed in this research from a pavement cost perspective. There are studies on the effectiveness of this concept from operational, safety and planning perspectives. Feasibility of funding such highways through tolls has also been addressed. Analysis of the cost component for truck-only lanes in this research adds more dimension in the ongoing discussion. This research analyzed the construction, rehabilitation, and right of way costs for the truck-only lanes approach. This foundation may help the agencies conduct similar analysis for certain routes and find the most efficient alternative for each route.

This research provides a preview of the highways with high market share of connected and autonomous vehicles. This methodology can be exploited for simulating diverse highway environments with heterogeneous traffic that carries any proportion of human driven cars, connected and autonomous cars, human driven trucks, and connected autonomous trucks.

One of the possible reasons for truck owners to invest on the connected and autonomous trucks would be to reduce fuel consumption cost and enhance safety benefit from truck platooning. This research showed how the current lane management policy can only deliver partial benefits from the fleet automation. It has explored some of the most probable policy options that may
ensure higher fuel consumption benefit from the connected and autonomous trucks. Highway agencies can consider these findings to decide future policy choices.

Reduction of future highway construction/reconstruction and rehabilitation costs is associated with the lane management approach for the connected and autonomous vehicles just like the existing vehicle fleet. But the future cost implications may seem more important as both the number of vehicles and highway lane miles are likely to increase. Highway agencies can use the cost reduction concepts to optimize future policy options and control the costs.

Finally, this research showed that reduction of fuel consumption cost by platooning of trucks on a highway is largely dependent on the availability of space for the trucks to maintain uninterrupted platoons for longer distance. Allowing truck platoons to find space large enough to maintain their formation would depend on the choice of lane management policy.

4.3 Recommendations for Future Research

This research has analyzed some possible lane management approaches and pavement design options that can reduce highway life cycle cost (LCC). One of the possible solutions to tackle the cost trends is to ensure more distribution of trucks across the available lanes in the highway system. Distribution of trucks is being practiced along some routes where truck lane restriction is not in full effect. It is possible to validate the findings with real life data from those locations where truck lane restriction is in full effect. Reversing truck lane restriction along routes where it is being practiced may not be a popular decision among the drivers of passenger cars in present context. However, widespread adoption of connected and autonomous vehicles in the near future may require agencies to promote truck platooning and subsequently, deviate largely from the existing truck lane restriction practice. With heavy dependence on machines for viewing the surroundings, driver discomfort to share lane with heavy vehicle may not be a significant barrier
in the future. Heterogeneous lane design is a new concept that has not been tested anywhere to the authors’ knowledge. In order to enhance cost efficiency of highways with this alternative, field tests should be conducted. Additional construction challenges and costs to tackle those for heterogeneous pavement lanes were ignored here. Additionally, heterogeneous lane design for rigid pavement can be a potential topic of future research.

Cost benefit of truck-only lanes approach reported in this research was for an assumed right-of-way price scenario in Florida. Similar exercise can be conducted for major freight routes with land prices along those routes to assess if the price advantage holds in general. As the land price in urban areas is generally higher than that in rural areas, a comparison can be made for each state between urban and rural areas to determine feasibility of truck-only lanes in the U.S. highway system. In areas where right of way expansion for truck-only lane is expensive, an assessment can be made if grade separation of the highway would enhance or reduce the cost efficiency.

Alternative lane management approaches to accommodate truck platoons in this research were analyzed for the entire life cycle. For example, no-platoon approach for a three-lane highway was compared to permitted platooning on one lane with a life cycle of 20 years. However, future lane management approach may be dynamic, instead of having static approach all the time. Same route may allow truck platooning on all the available lanes during the off peak period of the day or at a certain time of the year while allowing limited platooning on one lane during the peak traffic hour. Future studies can consider the traffic volume variation over time and can experiment with dynamic lane management based on available opportunity for the trucks to continue uninterrupted platoons. Such an experiment can reveal whether a mix of management approaches can provide higher benefits for future vehicles. Also it can determine the type of traffic and lane configurations that would suit a particular management approach or a certain mix of management approaches.
This research considered three highway lanes in one direction to assess the cost implications of truck platooning. This was done because three lanes were the minimum to compare all the management approaches presented here. Also the analysis was conducted for the median truck volume for a group of major freight routes in U.S. Future studies may pair the actual truck volume with the existing number of lanes along each freight route and assess possible lane management approaches. That should reveal how the highways with two lanes in one direction are different in terms of cost assessment from the highways with three or four lanes in one direction. Even among the two-lane (in one direction) highways, such analysis can reveal the impact of truck volume on LCC. The lane variation combined with the range of truck volume can provide a general understanding of how future LCC and especially fuel consumption of connected autonomous trucks may change.

It was assumed that the demand of truck platooning would depend on the lane management policy only. It was also assumed that only a fraction of trucks would participate in platooning movement when one out of three heterogeneous lanes (open to both passenger cars and trucks) in one direction would be opened for truck platooning but almost all the trucks would participate in platooning movement when a lane would be dedicated to truck platooning (not open for passenger cars). There may be other economic and transportation policy issues that would impact the demand of truck platooning. To understand how much fuel consumption benefit can be achieved from truck platooning, surveys can be conducted among the trucking companies that operate in the major freight routes. The survey can reveal the factors that determine the demand of truck platoons. It can also provide a more complete assessment of future highway LCC and whether truck platooning benefits will be enough to think about tolled truck-only lanes in the future.
References


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